$\Omega_{baryons} = 0.045 +/- 0.004 \sim (1/6)\ \Omega_{matter}$

Coronal & diffuse IG gas~0.037

Cluster IGM~0.002

Stars ~ 0.003

Cold Gas ~ 0.0008 (~2/3 atomic)

HI is a piffling fraction of cosmic matter, baryons

Fukugita & Peebles 2004

ALFALFA: The Arecibo Legacy Extragalactic HI Survey

Riccardo Giovanelli (Cornell University)

Fermilab Oct 09

ALFALFA

HI : Why do we care ?

- Optically thin → cold gas mass
- Good index of SF fertility
- Excellent tracer of host dynamics
- Interaction/tidal/merger tracer
- Can be dominant baryon form in low mass galaxies
- HI Mass, Diameter Function, missing satellites
- Diagnostic tool of cluster dynamics/evolution
- Peculiar velocity, mass density field
- Low z link to DLAs
- LSS, cluster, group structure, void/metallicity problem
- EoR

ALFALFA, a Legacy HI Survey

- One of several major surveys currently ongoing at Arecibo, exploiting its multibeam capability

- An extragalactic HI spectral line survey
- To cover 7000 sq deg of high galactic latitude sky
- 1345-1435 MHz (-2000 to +17500 km/s for HI line)
- 5 km/s resolution
- 2-pass, drift mode (total int. time per beam ~ 40 sec)
- ~2 mJy rms [M_{HI}~10^5 in LG, ~10^7 at Virgo distance]
- 4000 hrs of telescope time, spread over 6-7 years
- started Feb 2005; as of mid 2009, 70% complete

http://egg.astro.cornell.edu/alfalfa

ALFALFA

ALFALFA, a Legacy HI Survey

- One of several major surveys currently ongoing at Arecibo, exploiting its multibeam capability

- An extragalactic HI spectral line survey

The Arecibo Legacy Fast ALFA Survey

Main People Science Schedule Data Documentation Links Publications Undergrads Non-experts News/Events Observing/Data Team

Overview

Arecibo is the world's most sensitive radio telescope at L-band. In addition to that all-important sensitivity advantage, Arecibo equipped with ALFA offers important and significant improvements in angular and spectral resolution over the available major wide area extragalactic HI line surveys such as HIPASS and HIJASS. To break ground into new science areas, extragalactic HI surveys with ALFA must exploit those capabilities to explore larger volumes with greater sensitivity than have the previous surveys. The lowest mass objects will only be detected nearby; wide areal coverage is the most efficient means of increasing the volume sampled locally. An extragalactic survey covering the high galactic latitude sky visible from Arecibo will produce an extensive database of HI spectra that will be of use to a broad community of investigators, including many interested in the correlative mining of multiwavelength datasets; we thus dub this program the Arecibo Legacy Fast ALFA survey: ALFALFA. A comparison

Who is ALFALFA?

ALFALFA is an open collaboration: anybody with a valid scientific interest can join.

For participation guidelines, see:
http://egg.astro.cornell.edu/alfalfa/joining.php

Recommended guidelines for authorship can be found at:
http://egg.astro.cornell.edu/alfalfa/projects/authorshipguidelines.php

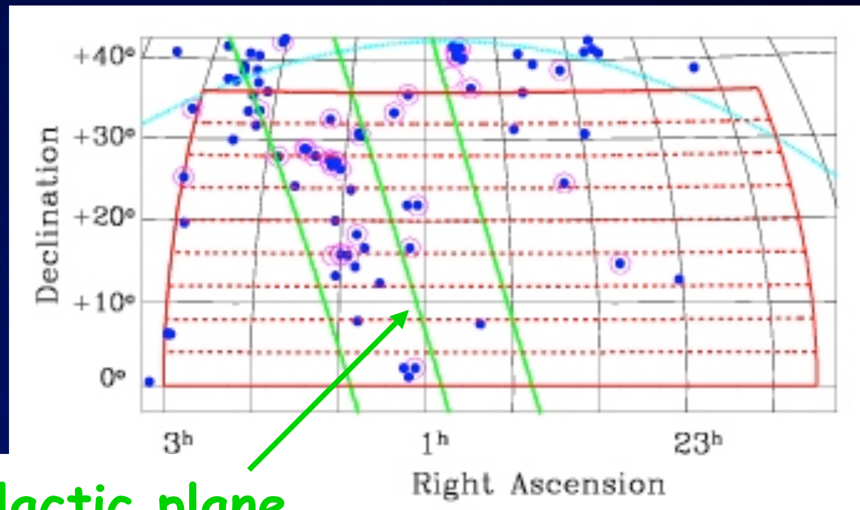
Project Guidelines: http://egg.astro.cornell.edu/alfalfa/projects/projectguidelines.php

Projects (Team/PhD/undergrad): http://egg.astro.cornell.edu/alfalfa/projects/projects.php

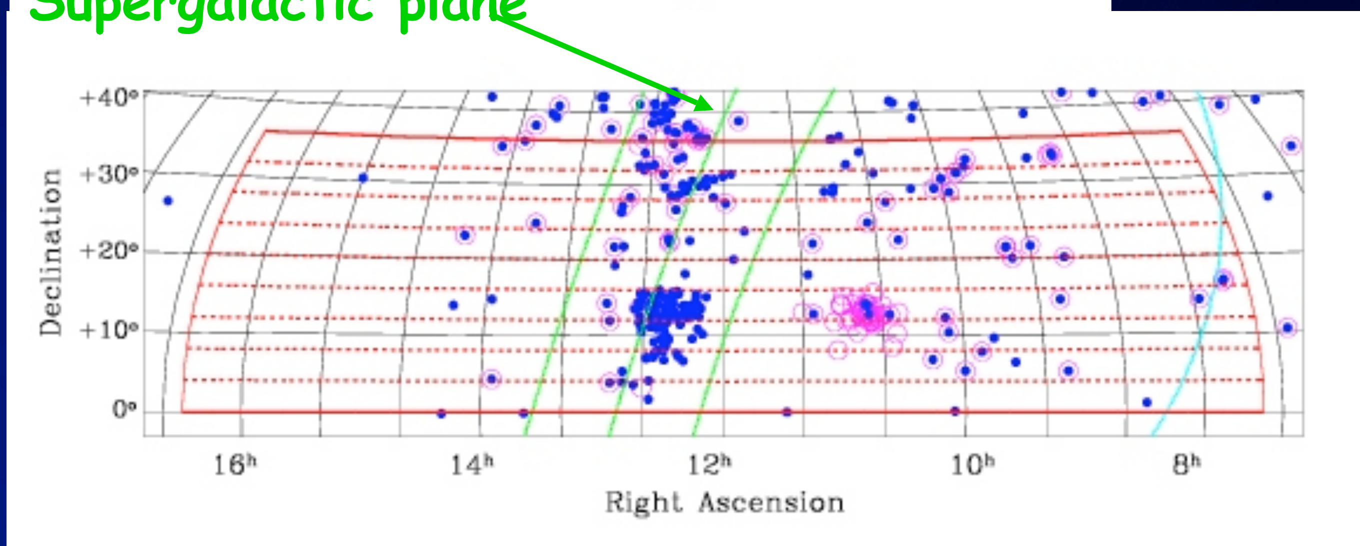
ALFALFA

ALFALFA Sky Coverage

High galactic latitude sky visible from AO



Supergalactic plane



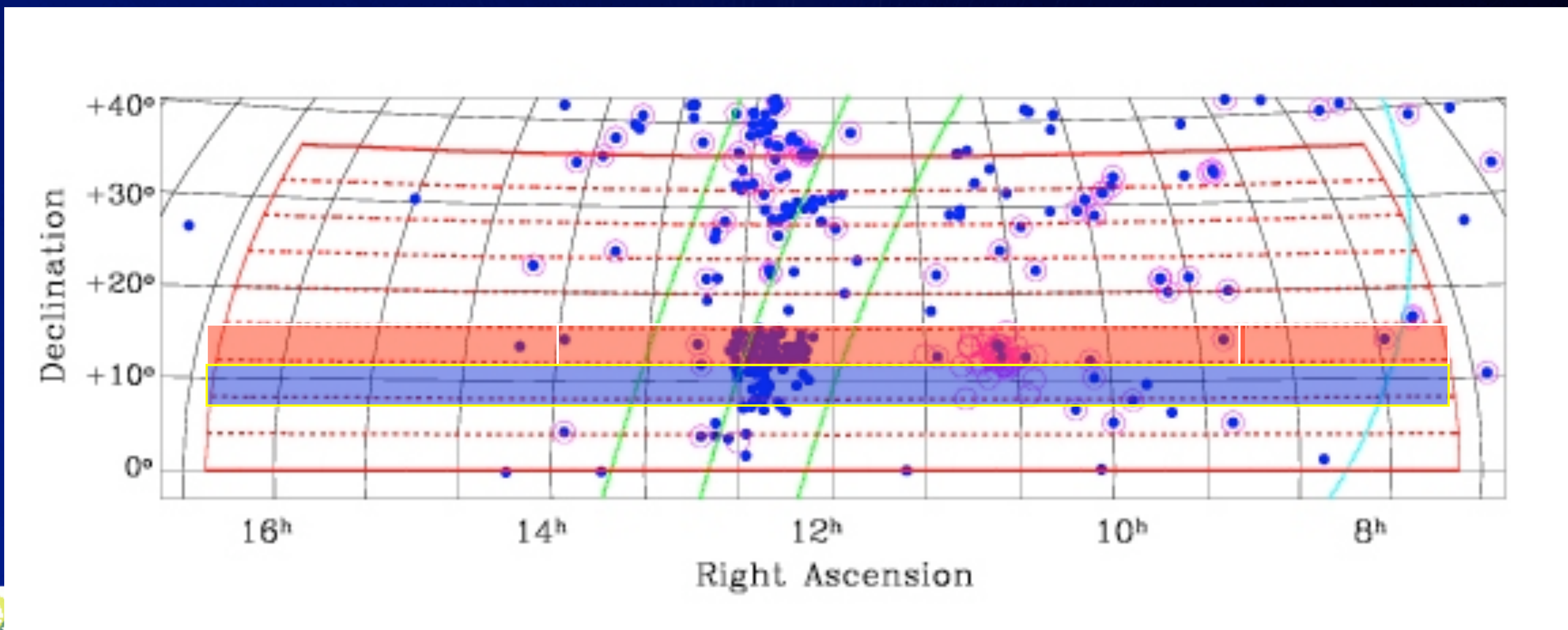
Comparison of blind HI surveys

Survey	Beam arcmin	Area sq. deg.	rms (mJy @ 18 km/s)	min M_{HI} @ 10 Mpc	N_{det}	t_s sec	N_{los}
AHISS	3.3	13	0.7	2.0×10^6	65	var	17,000
ADBS	3.3	430	3.3	9.6×10^6	265	12	500,000
HIPASS	15.	30,000	13	3.6×10^7	4315	460	1.9×10^6
HIJASS	12.	(TBD)	13	3.6×10^7	(?)	3500	(TBD)
J-Virgo	12	32	4	1.1×10^7	31	3500	3200
HIDEEP	15	32	3.2	8.8×10^6	129	9000	2000
ALFALFA	3.5	7,000	1.7	4.4×10^6	25,000+	40	7×10^6

ALFALFA is ~ 1 order of magnitude more sensitive than HIPASS with 4X better angular resolution, 3X better spectral resolution, and 1.6X total spectral bandwidth

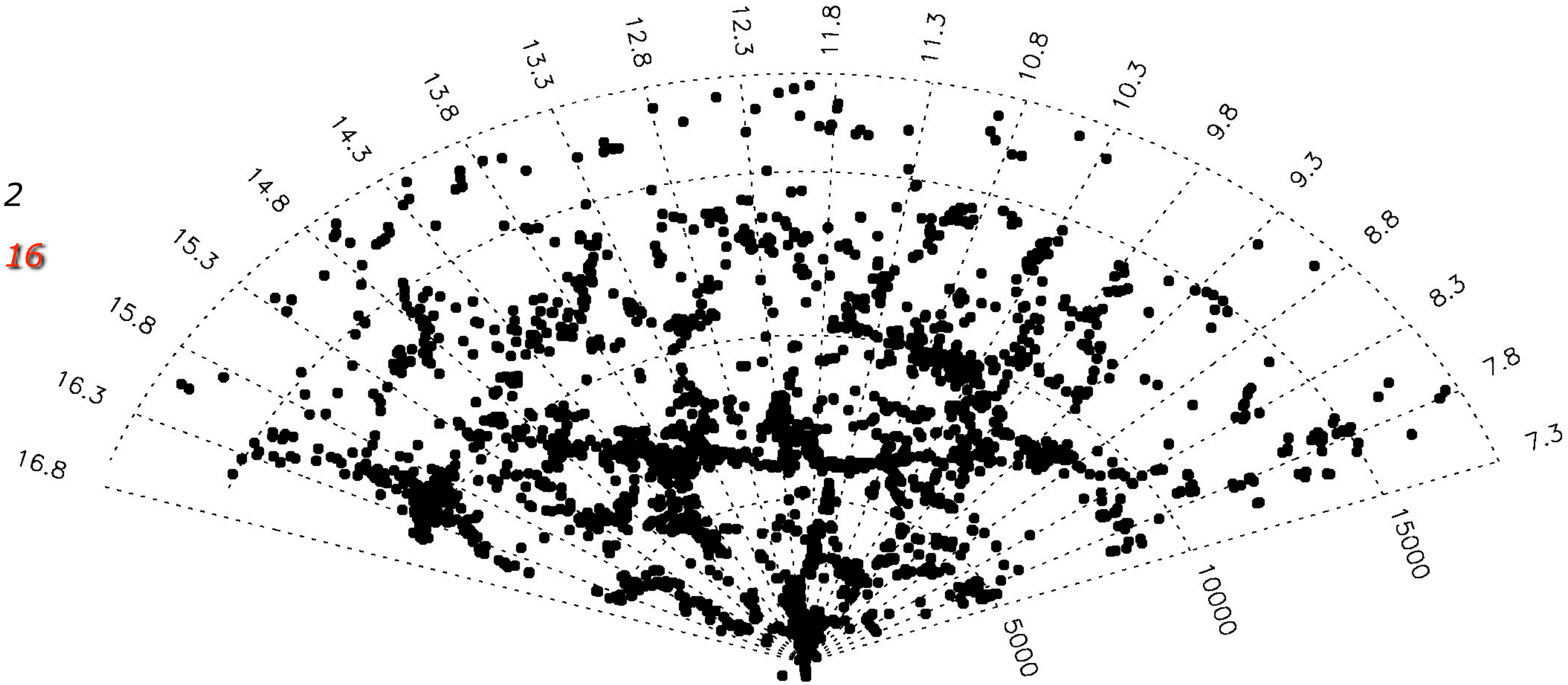
ALFALFA: 2 strips through Virgo

RA: 07:40h to 16:30h
Dec: 12deg to 16deg and
08deg to 12deg
Solid Angle: 1028 sq deg
(15% of survey)



Dec 8 to 12

Dec 12 to 16



ALFALFA

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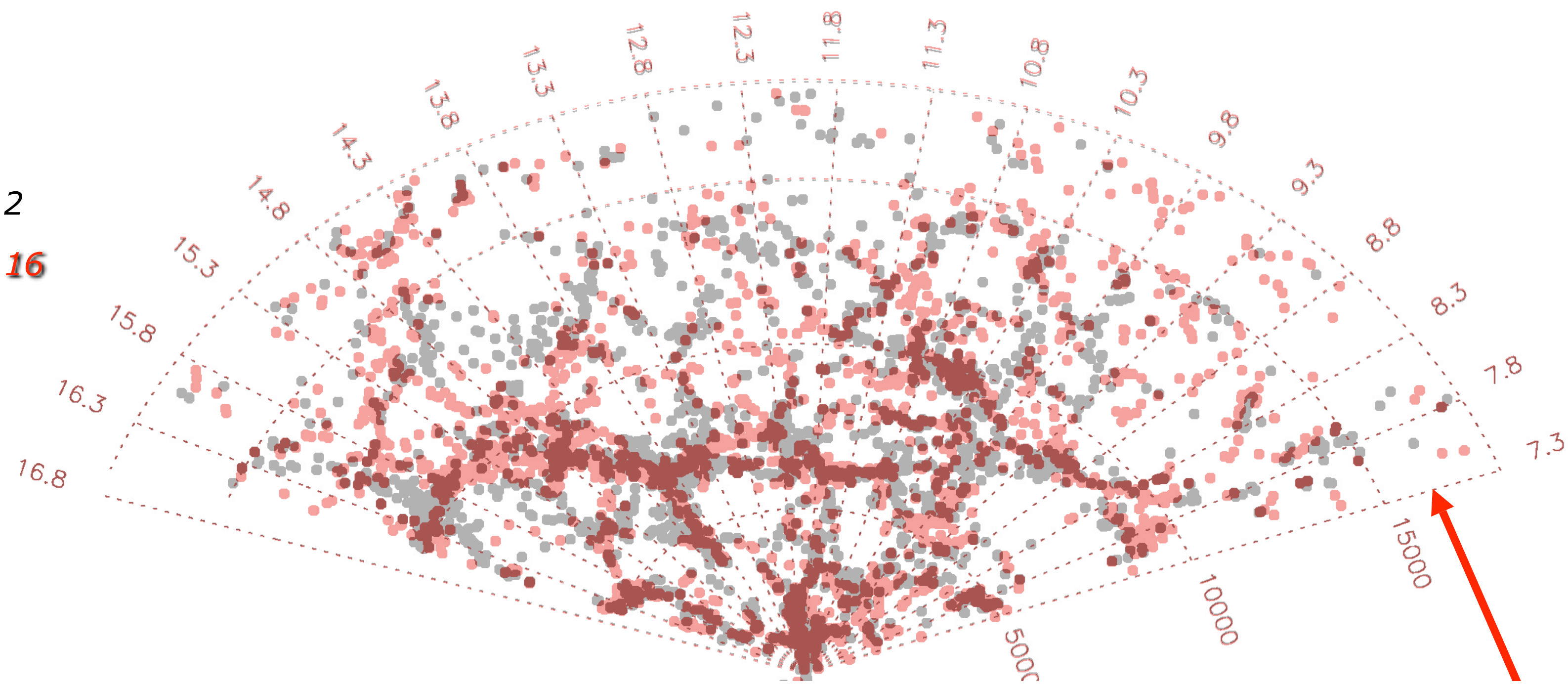
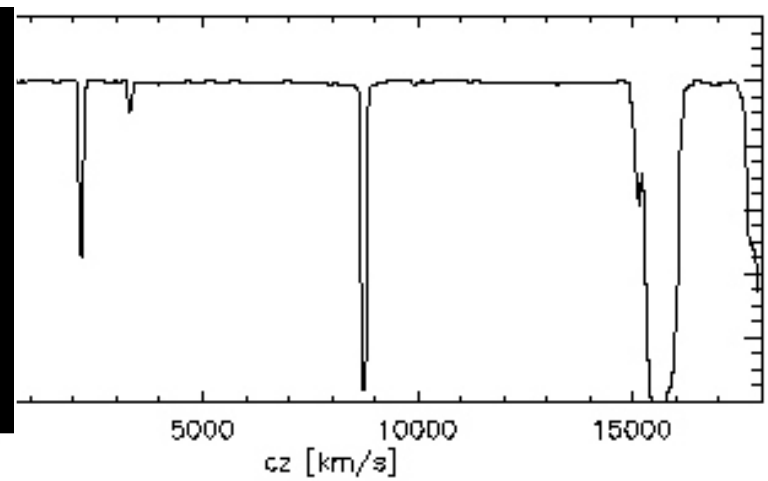


Over the ~1000 sq. deg. including the northern part of Virgo :

➔ ALFALFA detects 5200 sources, HIPASS 178 (several unconfirmed)

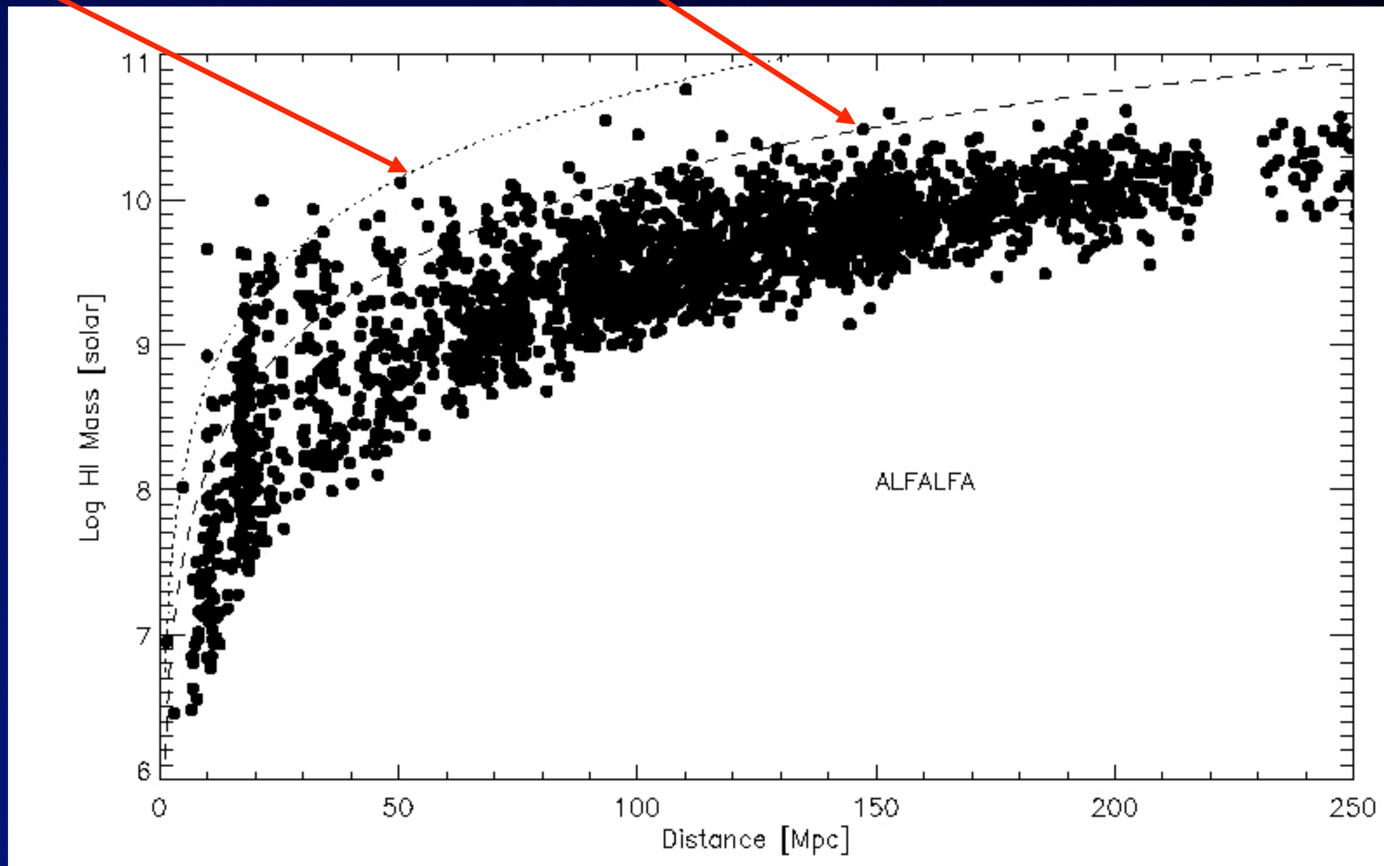
➔ While this region is perhaps the most intensively studied in the local Universe, at all wavelength bands (including HI, using optically selected samples),

➔ 69% of ALFALFA detections are new (the conventional wisdom on which optical targets would turn out to be HI-rich appears to have been limited)



HIPASS Completeness Limit

HIPASS Limit



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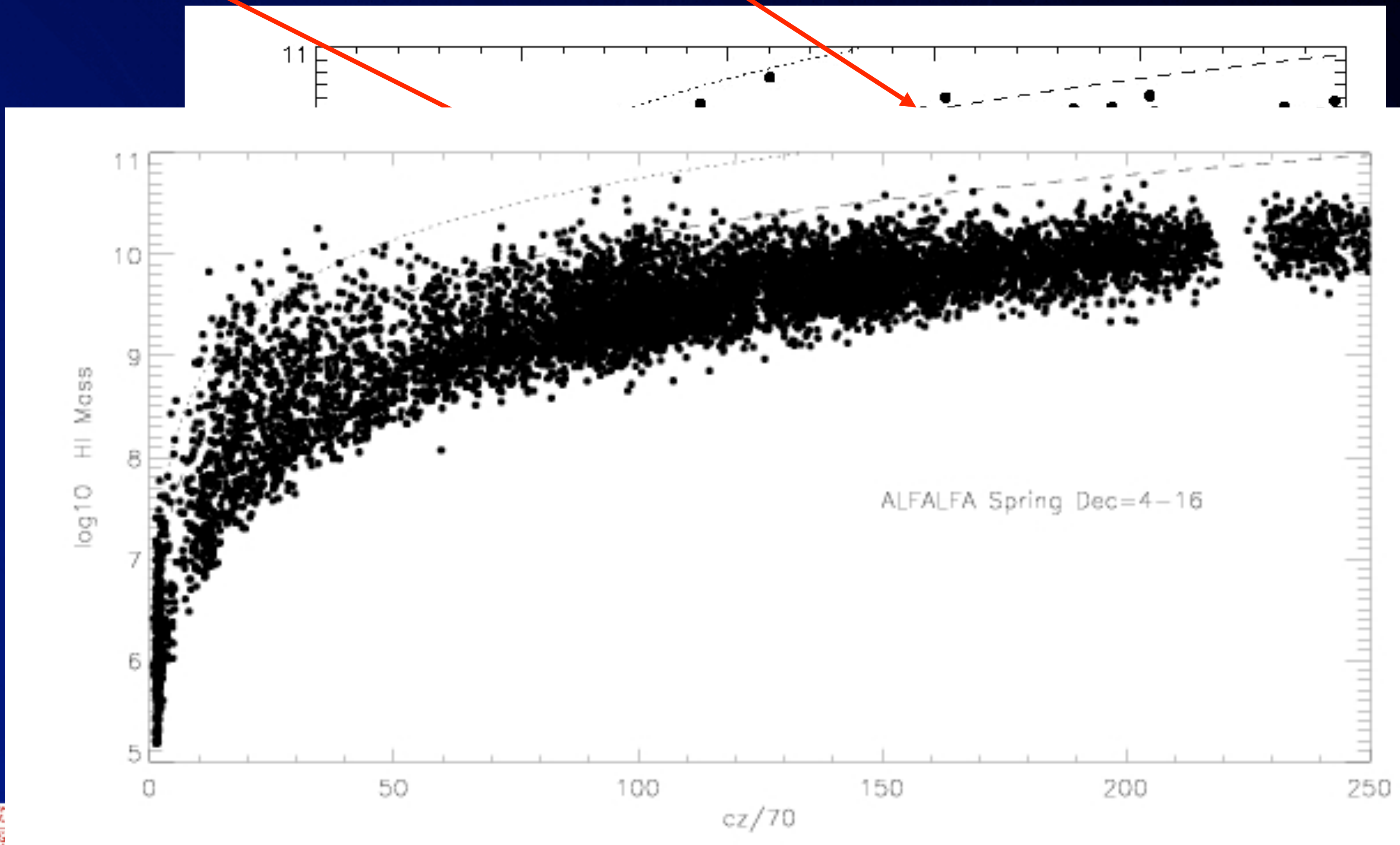
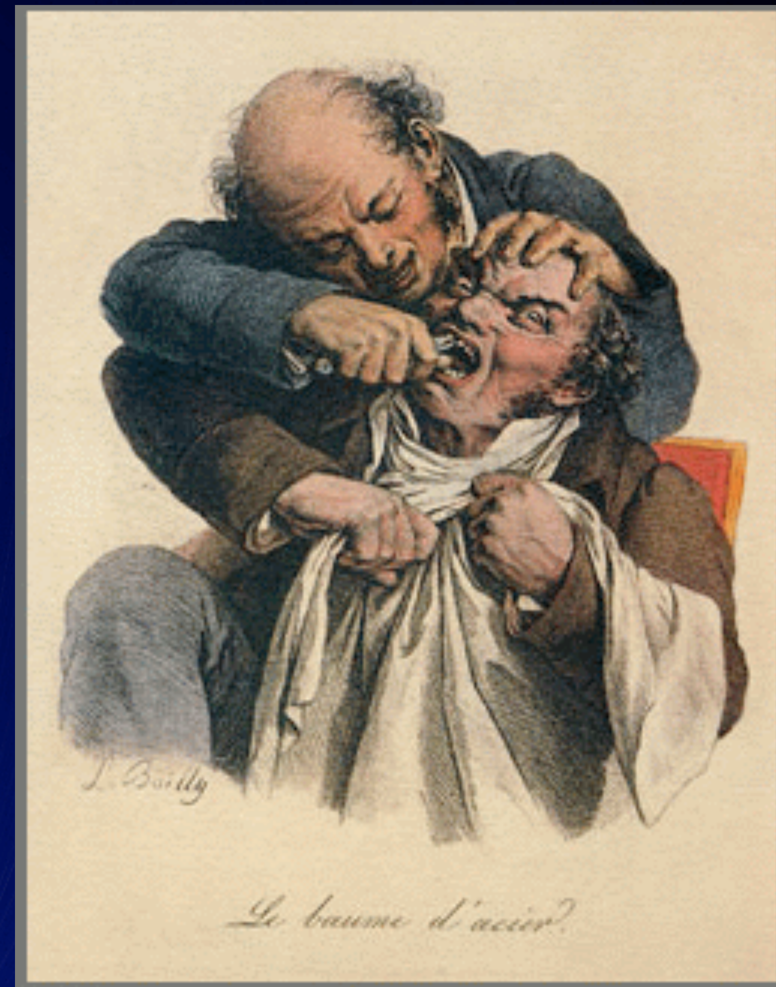


ALFALFA

Source extraction and identification of counterparts at other wavelength regimes can be a painful experience…



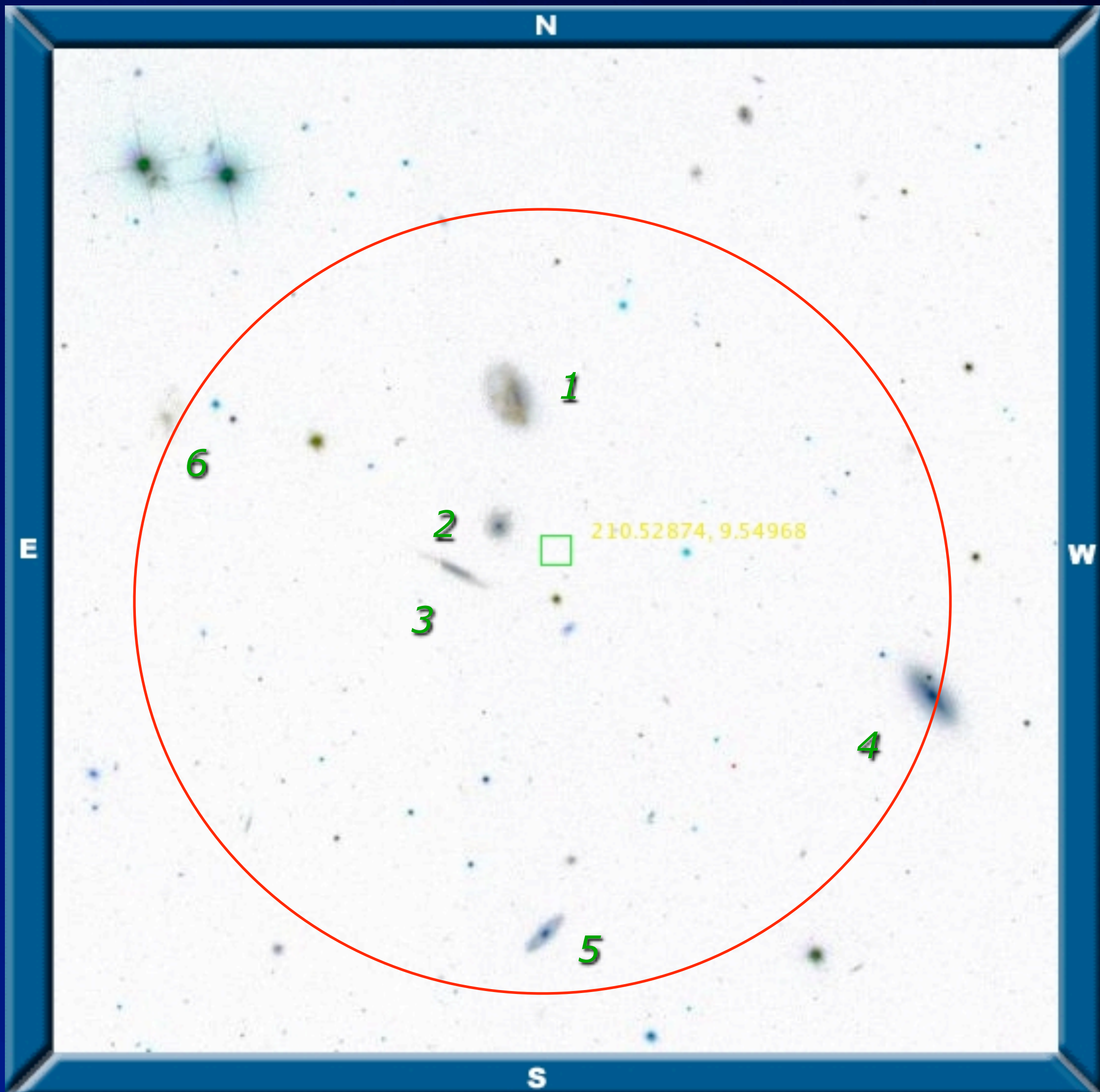
Source extraction and identification of counterparts at other wavelength regimes can be a painful experience…

...source centroiding as accurately as possible is thus highly desirable

ALFALFA

Centroiding accuracy goes roughly as

HPFW(PSF)/(S/N)



Centroiding accuracy goes roughly as

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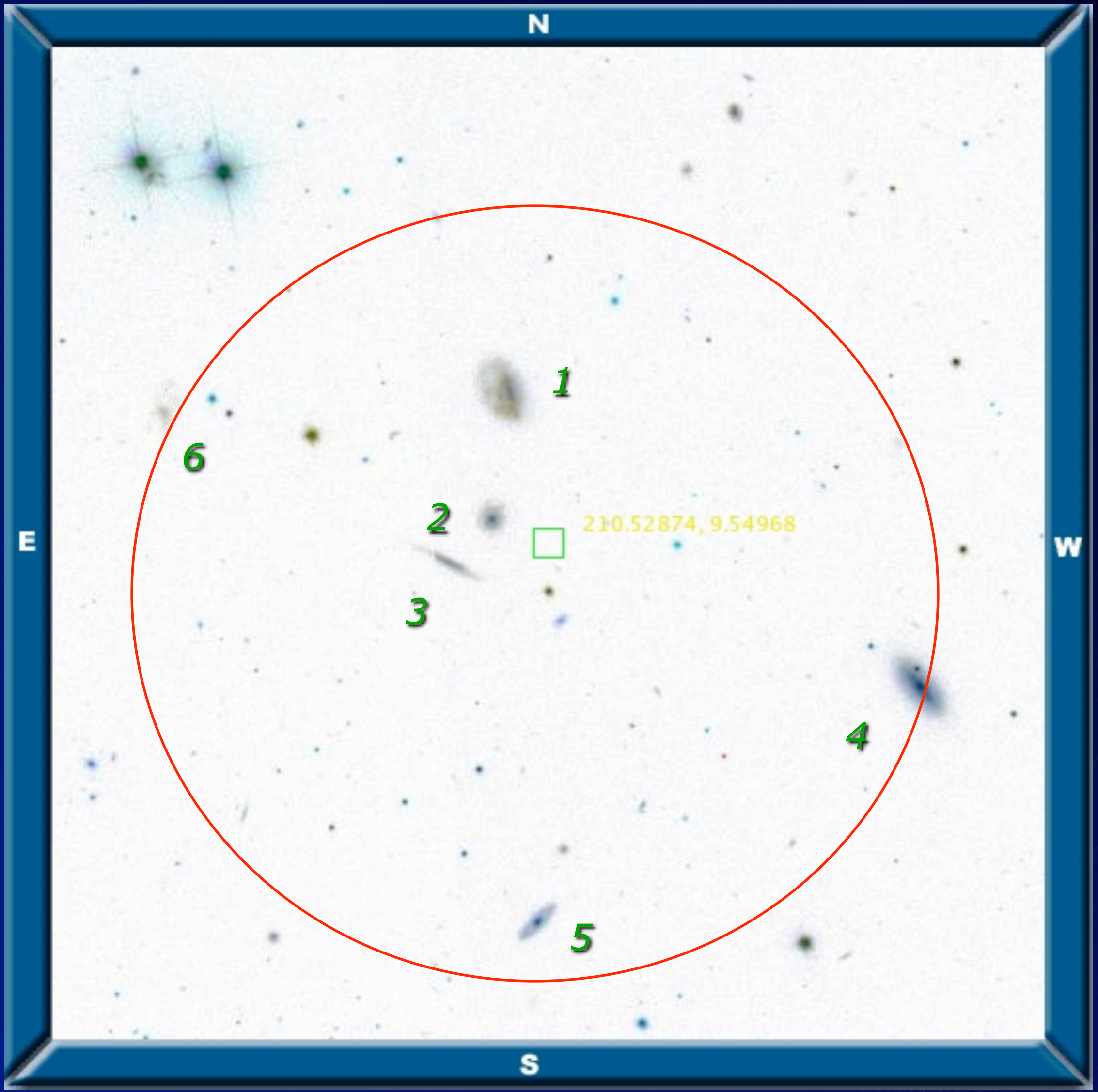
Suppose HIPASS detects a source at S/N~6 near 3000 km/s in this field. The position error box will have a radius of ~2.5′.

The opt counterpart could be gal #1, 2, 3, 4, 5 or 6.



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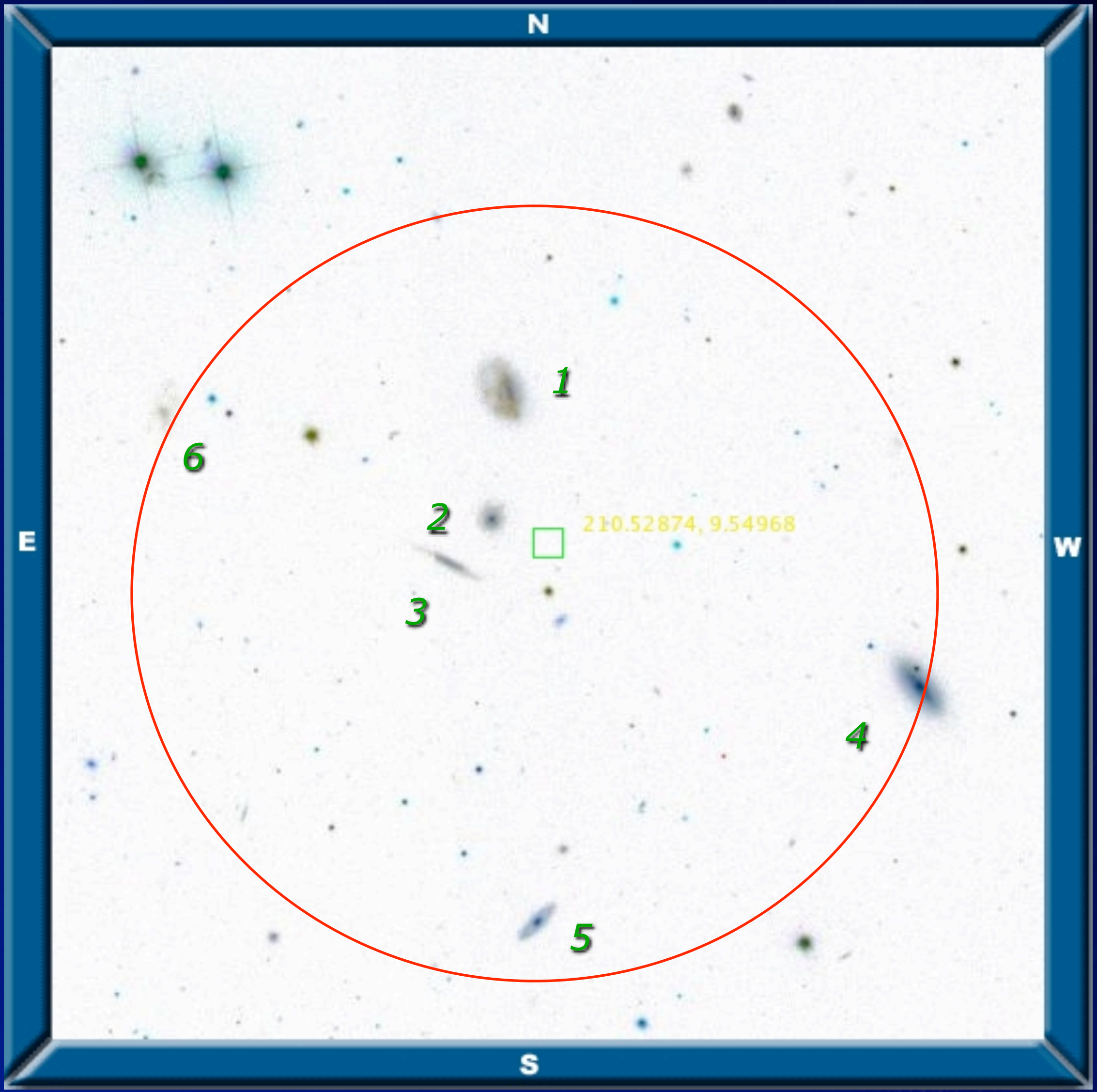

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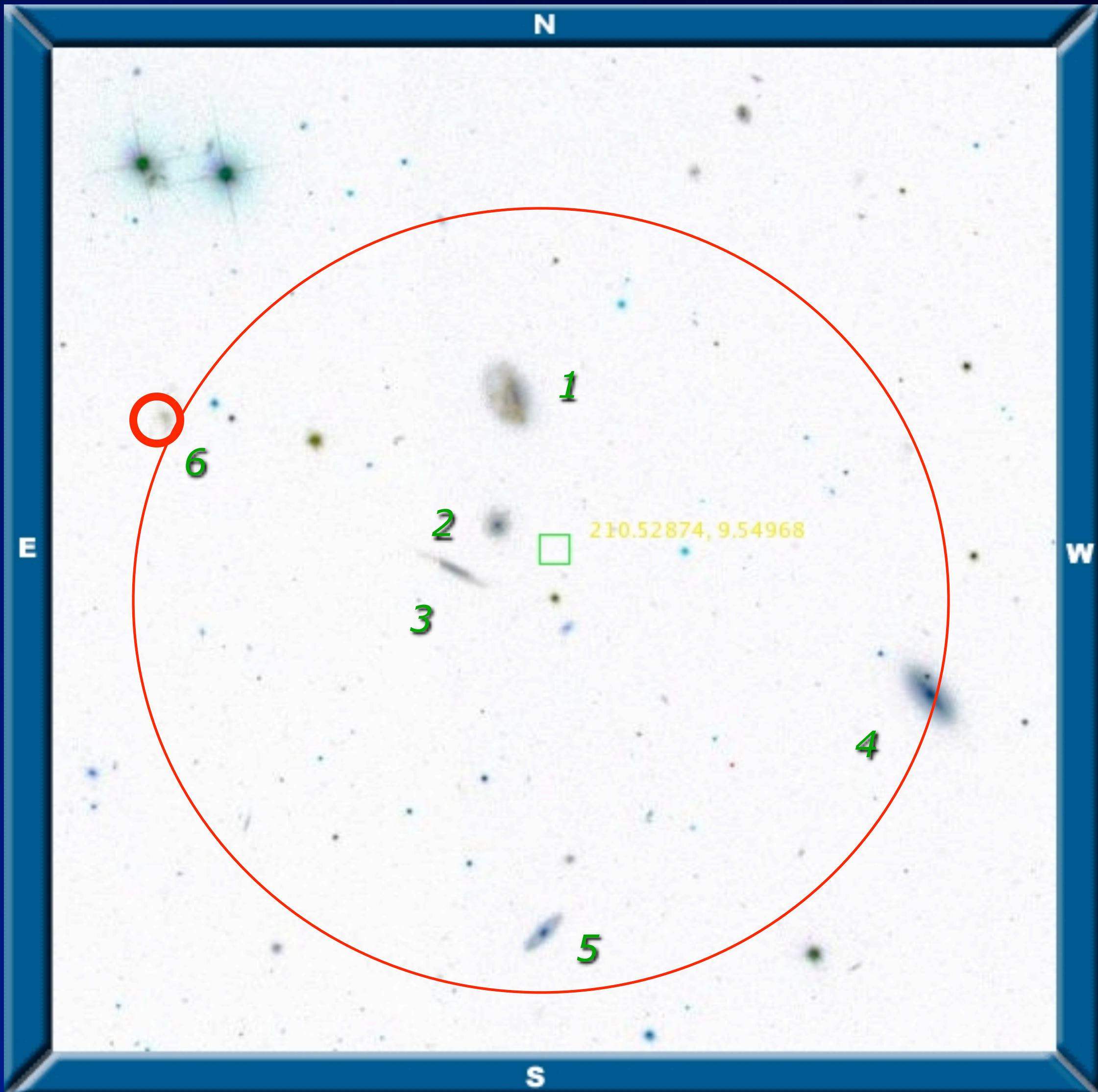

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➔ *The same source will have an ALFALFA position error of ~ 0.1′*

ALFALFA

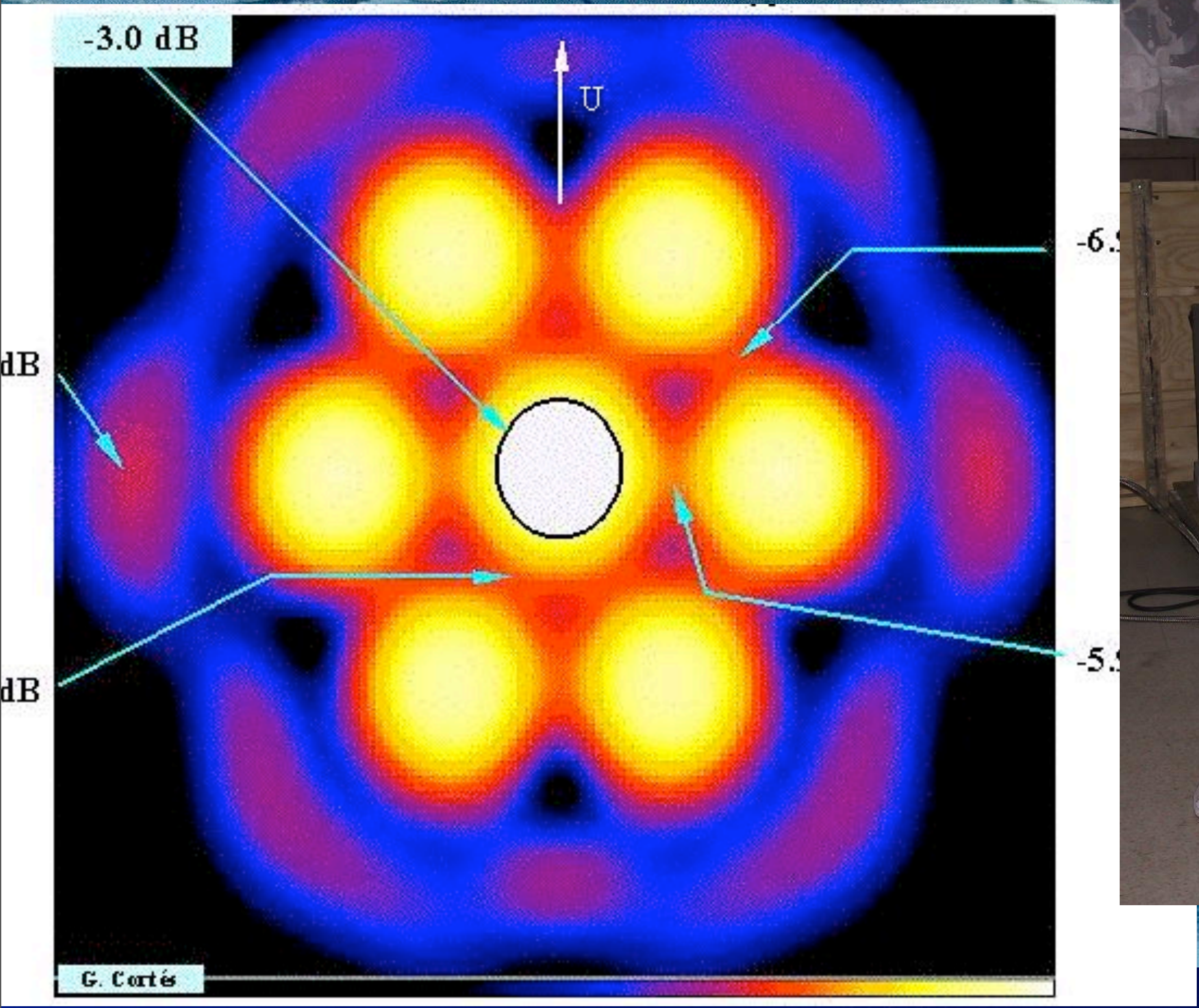
The Arecibo Telescope

ALFALFA

"minimum intrusion" approach

ALFALFA

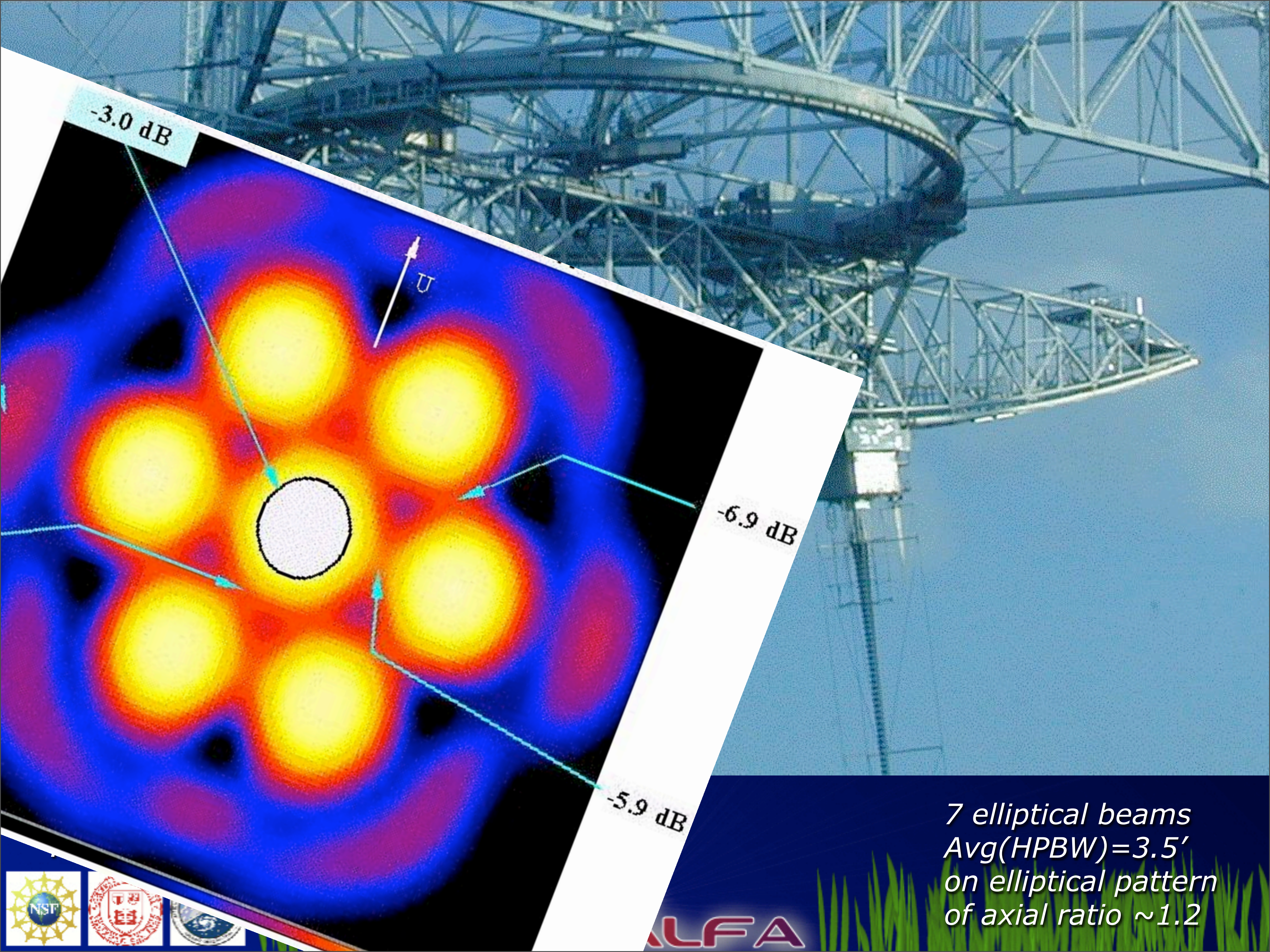
"minimum intrusion" approach



"minimum intrusion" approach

7 elliptical beams
Avg(HPBW)=3.5′
on elliptical pattern
of axial ratio ~1.2

ALFALFA



ALFA

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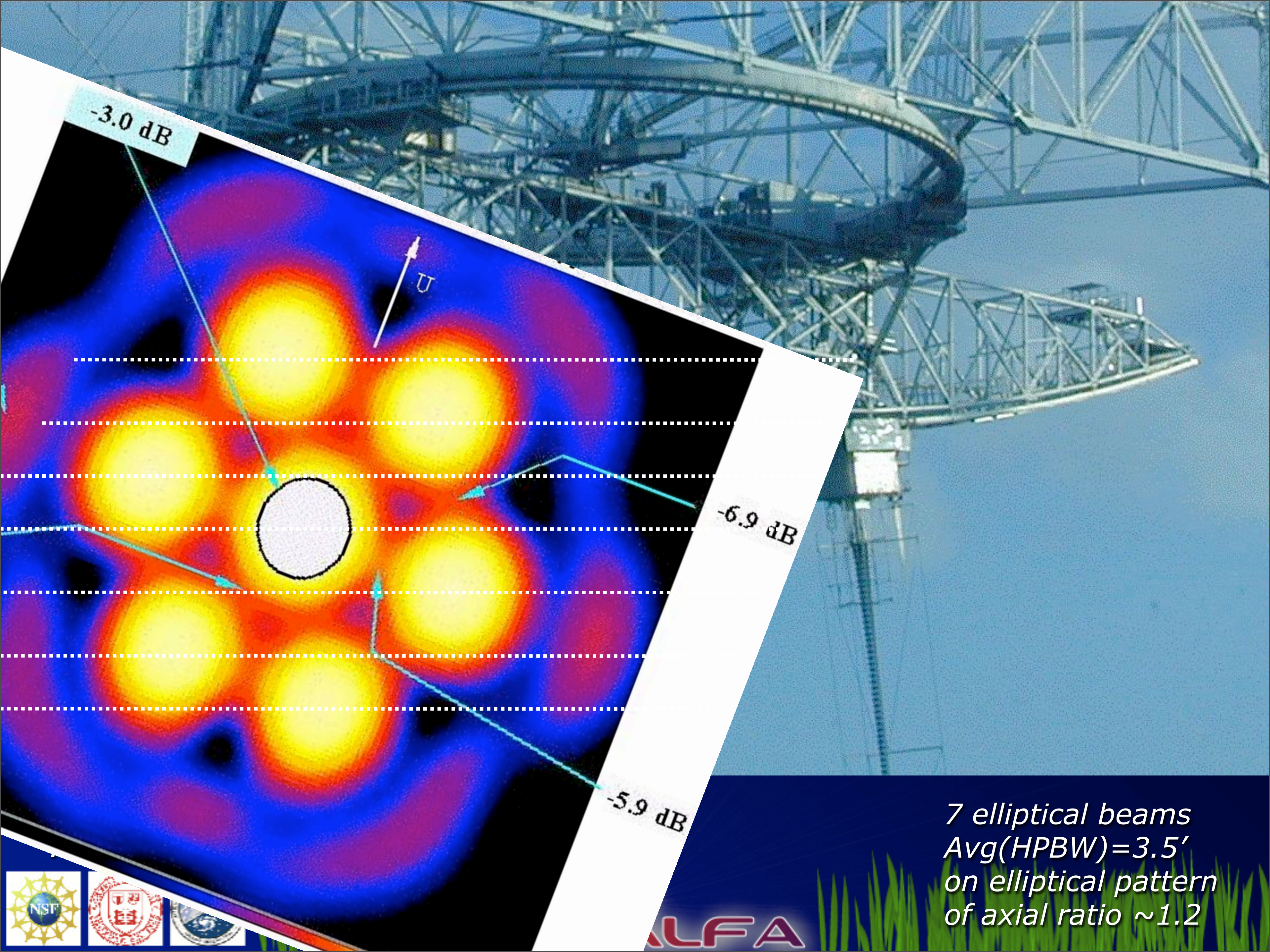

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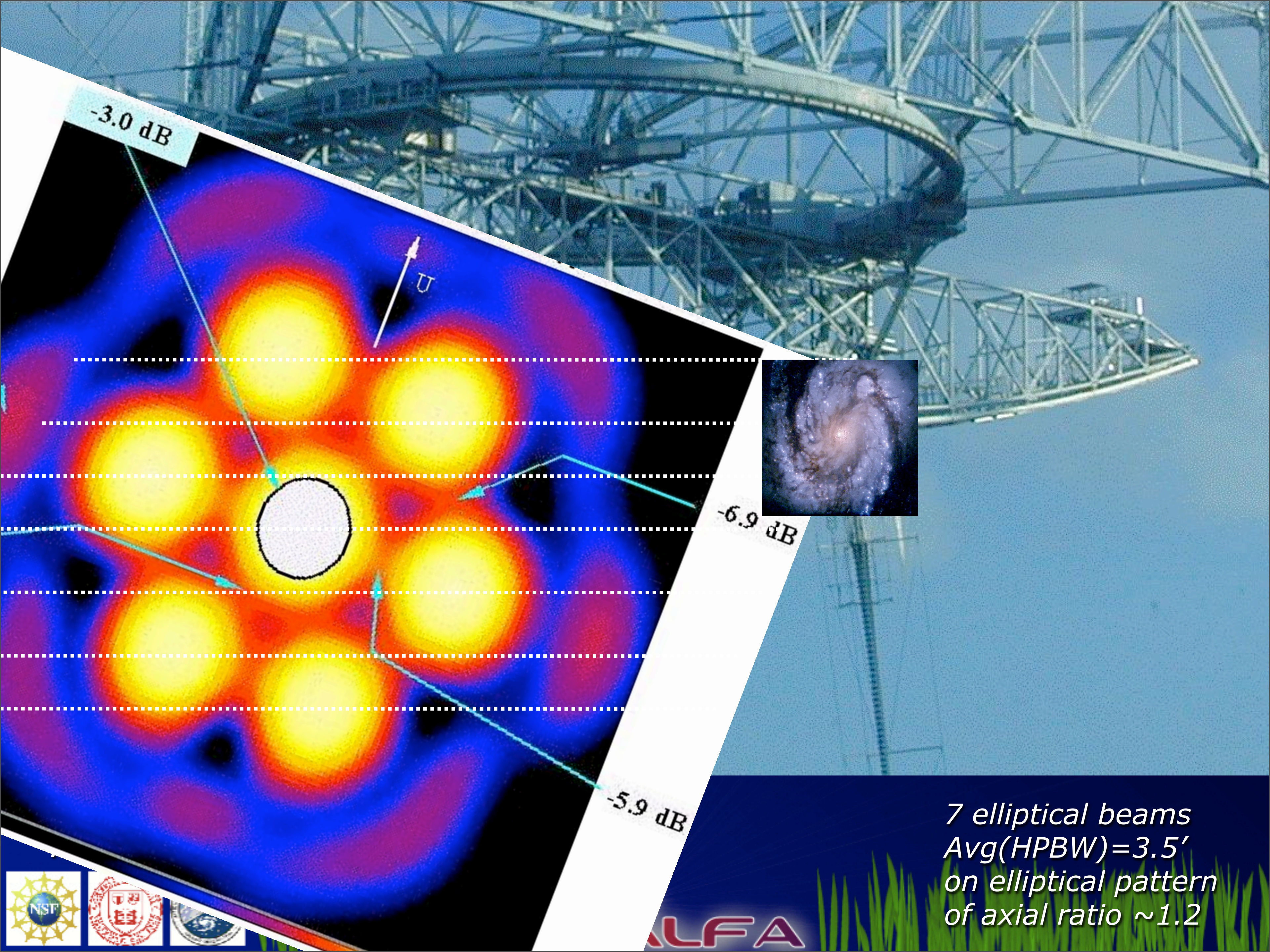

7 elliptical beams
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•"Minimum intrusion" approach on data taking (night time); "two-pass" strategy v important

•Data processing on fully home-grown software in IDL environment

STATUS @ Sep'09

•75% of data acquired (585 observing runs)

•60% of data processed to "level 2" (pre-grid)

•30% of data fully processed, catalogs produced:

Spring (RA = 07:30 to 16:30):

Dec strips +5 +7 +9 +11 +13 +15 +27

Fall (RA = 21:30 to 03:30):

Dec strips +15 +25 +27 +29 +31

ALFALFA data products can be accessed through the web using robust, NVO-compatible software tools, developed by our students, thanks to an NSF/NVO development grant and the archival support of the Cornell Theory Center.

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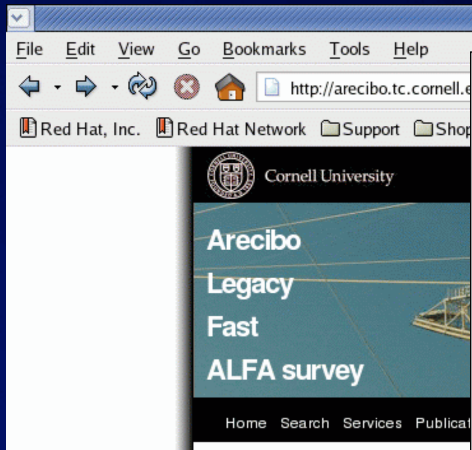
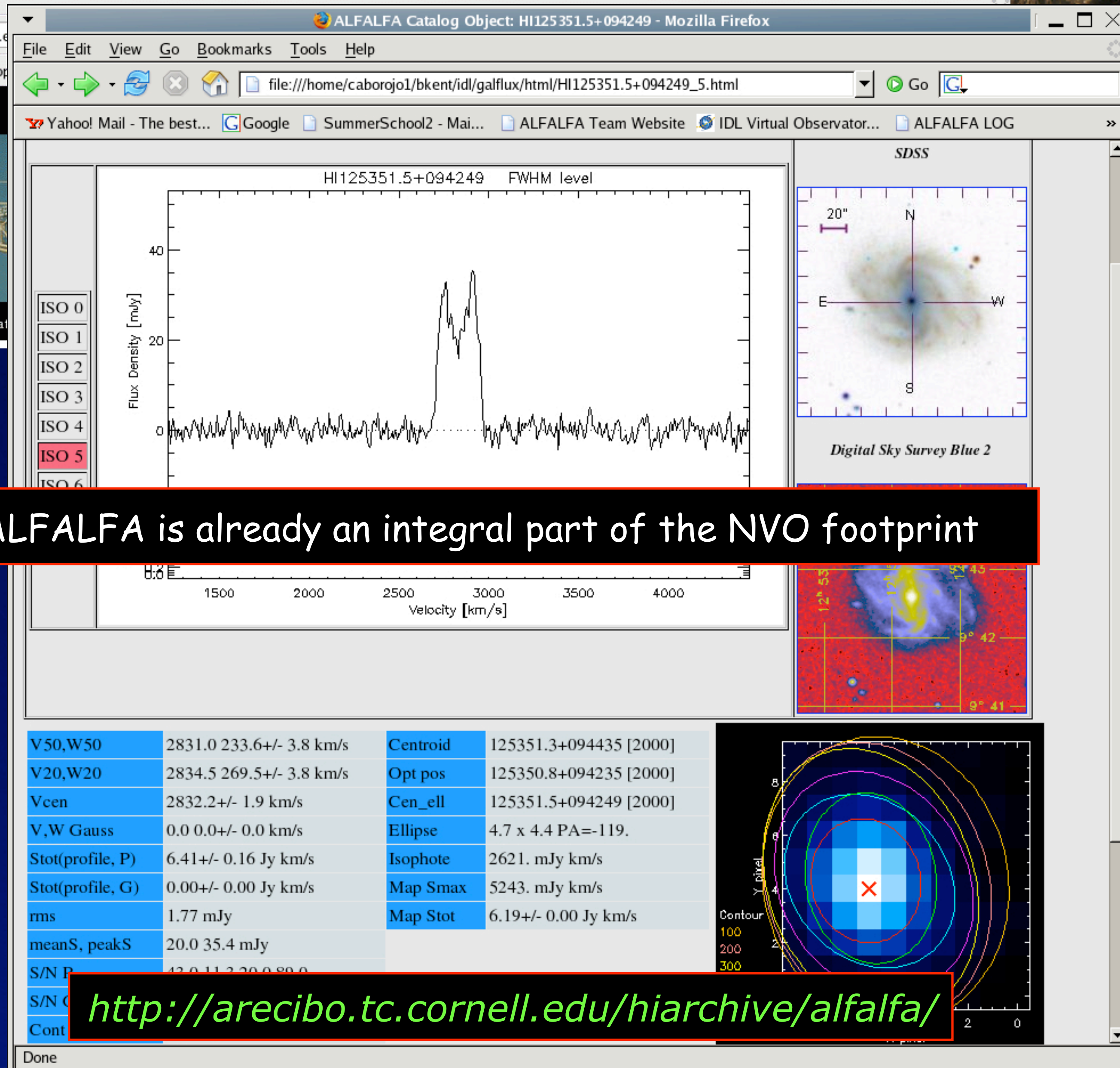


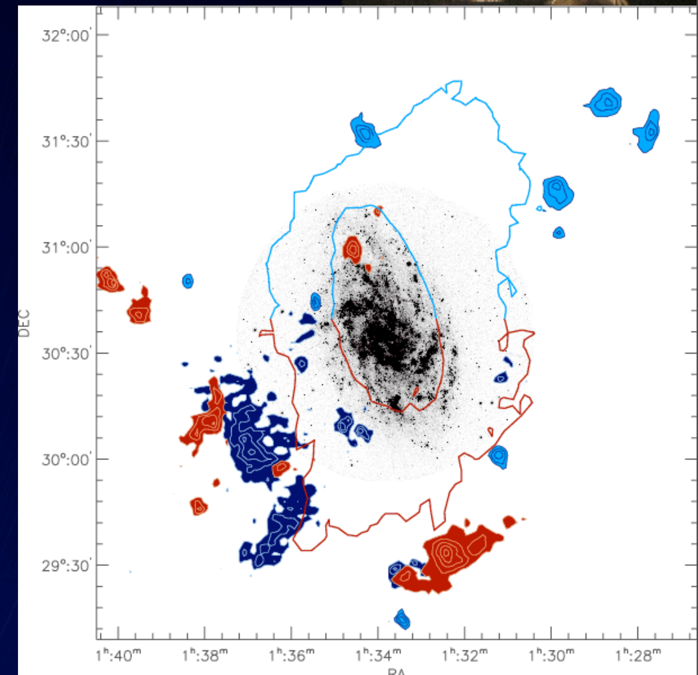


ALFALFA is already an integral part of the NVO footprint

http://arecibo.tc.cornell.edu/hiarchive/alfalfa/

Some ALFALFA highlights:

- Clouds around M33 (Grossi et al 2008)
- Intergalactic clouds in Virgo (Kent et al 2007; Kent et al 2008)
- VirgoHI21 is NOT a starless galaxy (Haynes et al 2007)
- Cluster Harassment episodes (Koopmann et al 2008)
- Leo Group HI Mass Function (Stierwalt et al. 2009)
- HI in ETGs (Di Serego Alighieri et al. 2007,2009)
- HI/Halpha in Virgo (Gavazzi et al. 2007)



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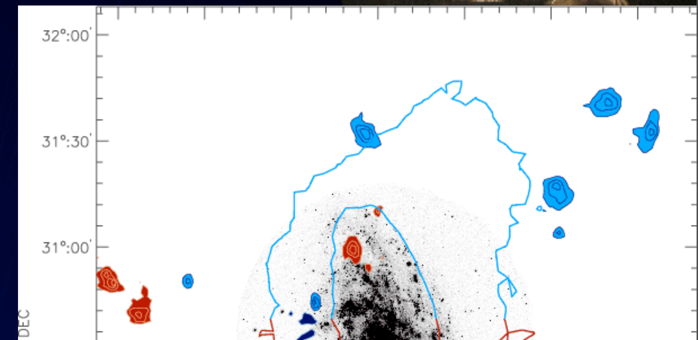

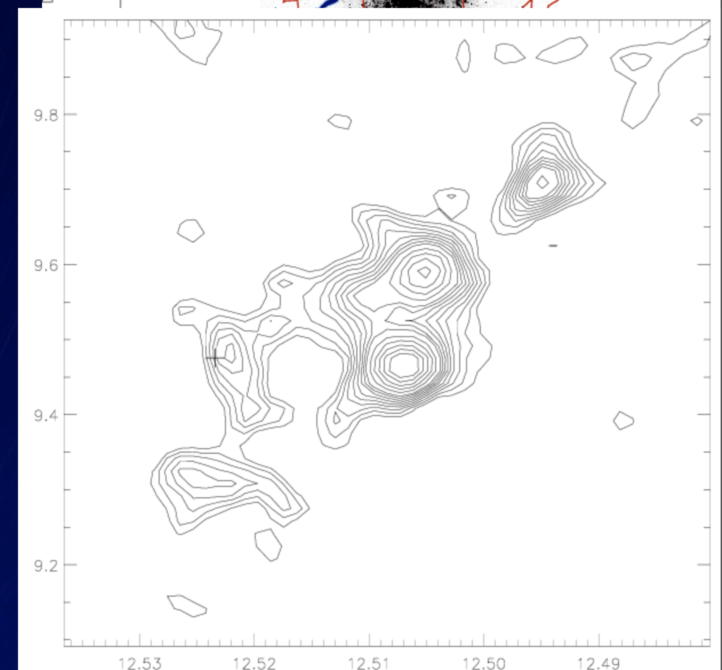

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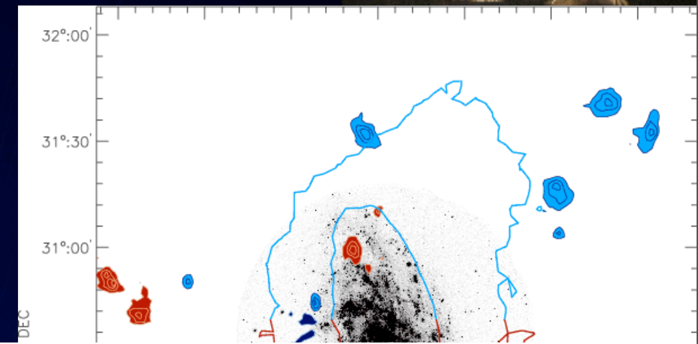
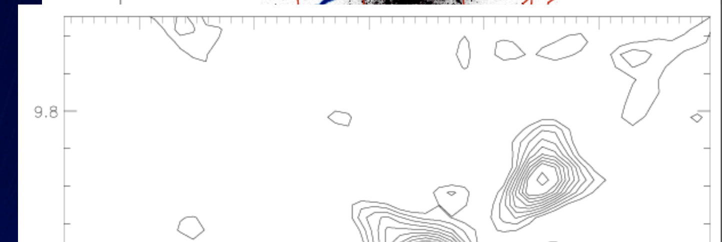
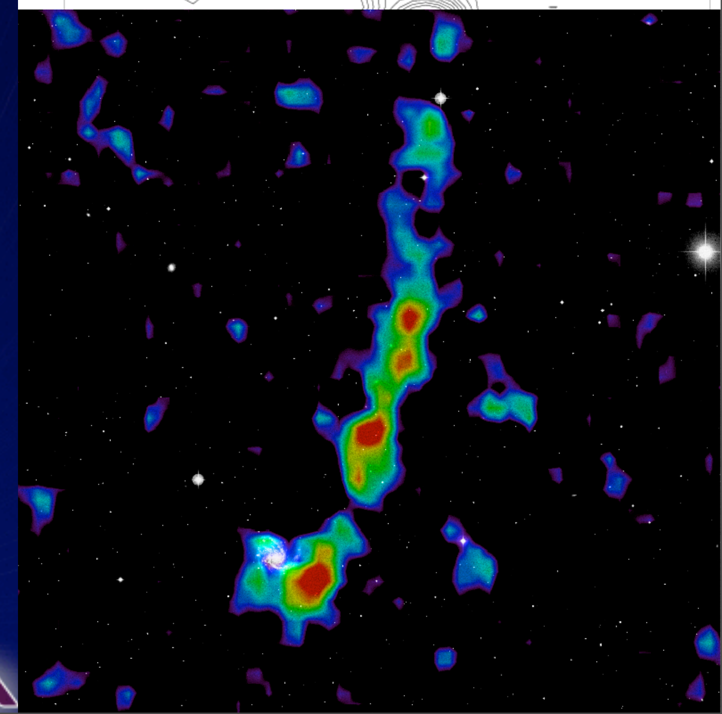
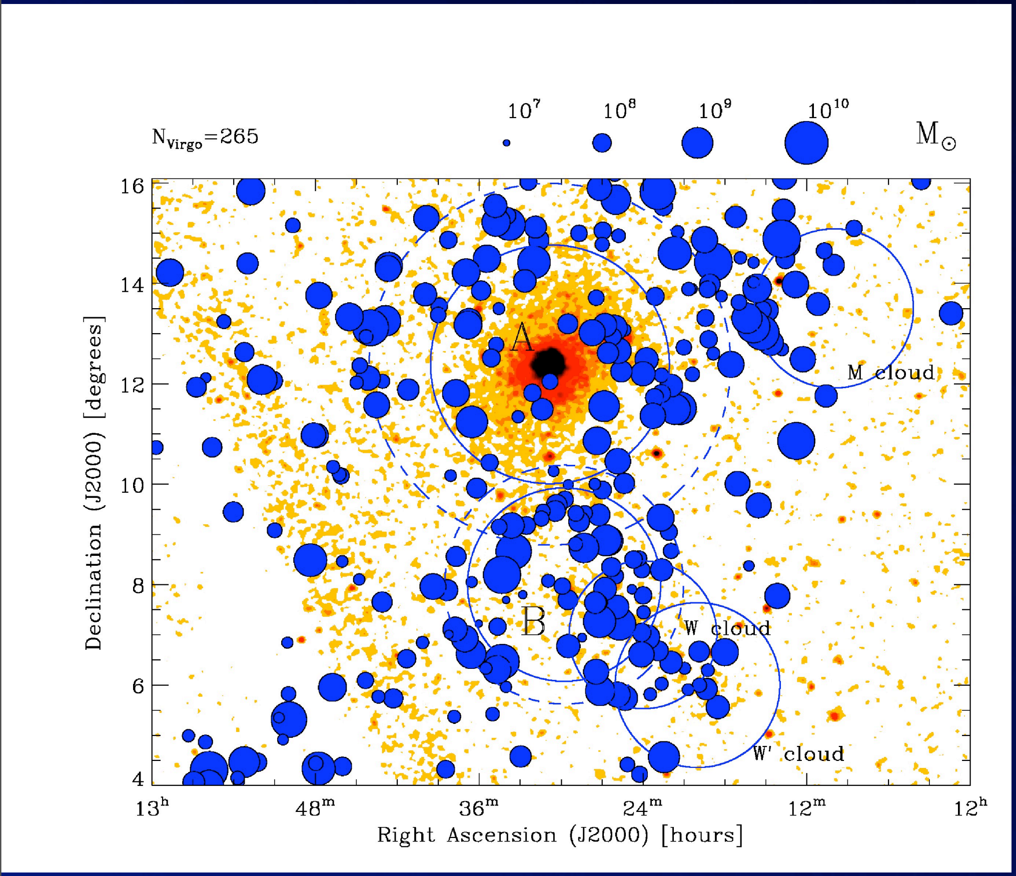


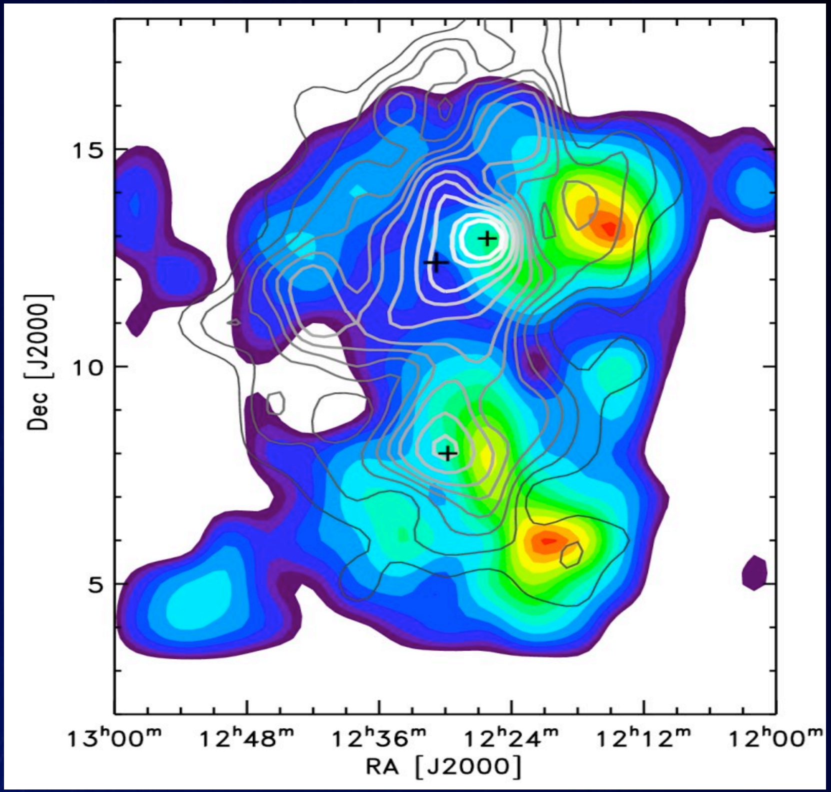




The Faces of Virgo



Credit: Brian Kent



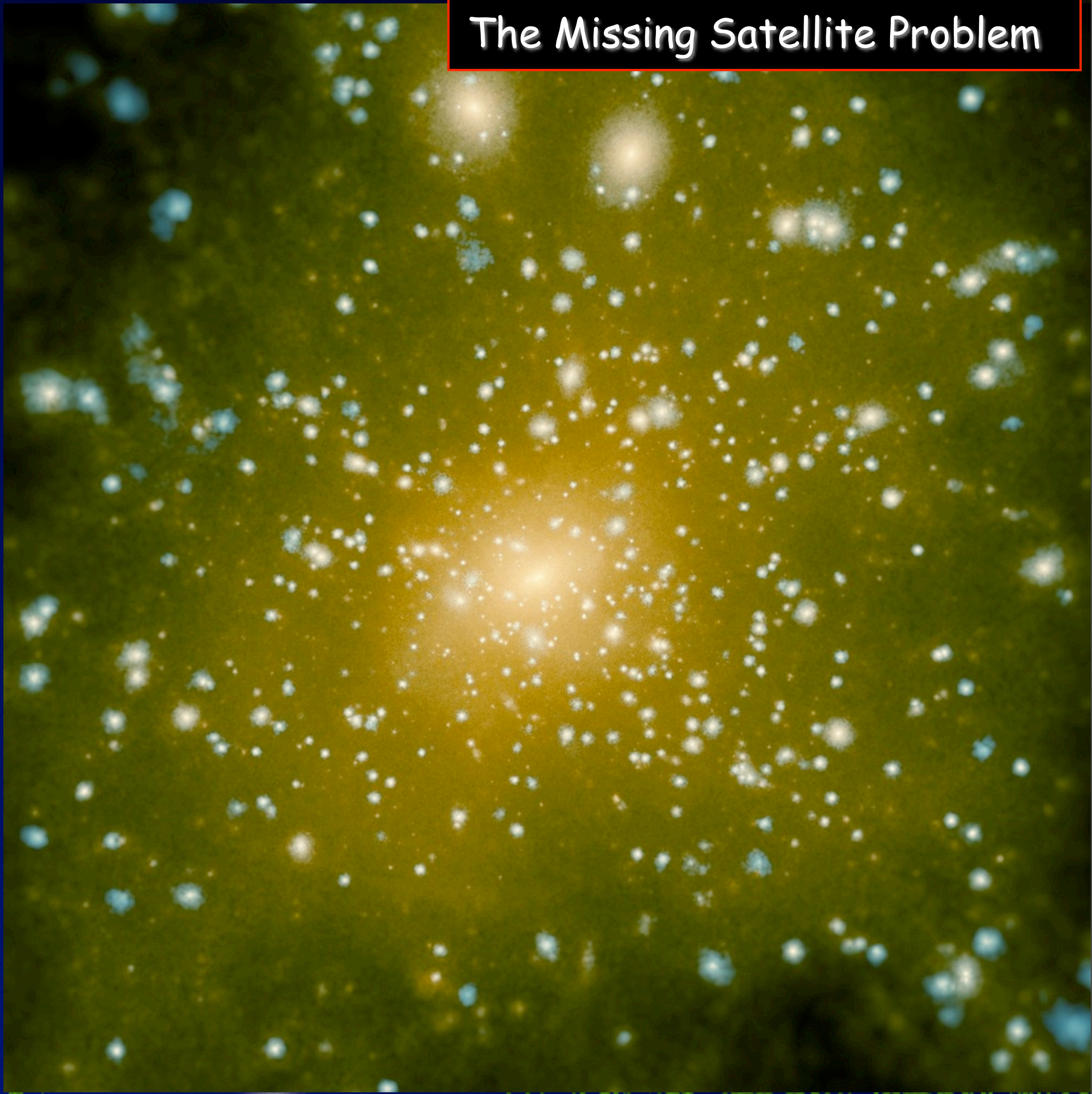
Credit: Amelie Saintonge

The Missing Satellite Problem

Numerical simulations predict the existence of lots of low mass halos:
Do they exist in the expected numbers?

Klypin et al 1999

- Are baryons in small Dark Matter halos fried at the epoch of reionization?
- Are they blown away by the first generation of stars?
- Is gas accretion & cooling impeded in low M halos?
- Are baryons retained but unable to make stars?
- Is that more likely in Cosmic Voids?



Credit: Virgo collaboration (MPIfAp)

The Void Problem

*Scenario set by **Peebles 2001**:*
-LCDM simulations show voids not being empty: they contain lower mass halos that "seem to be capable of developing into observable void objects"
-Observations, however, seem to indicate that the spatial distribution of dwarf galaxies is remarkably similar to that of brighter galaxies
➔ faint galaxies do not show a strong
tendency to fill the voids, so…

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This guy is a vapid bore…I had more fun before…when I had 7 roommates…

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with Snow White we ask

Where are the Dwarfs?

Disclaimer: this is NOT part of Jim Peebles' paper

ALFALFA

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➔ fa
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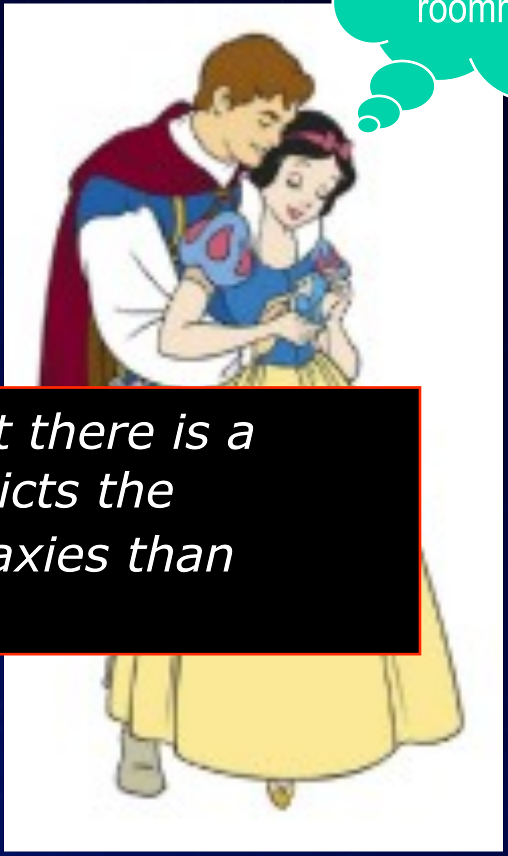
The key assumption, in saying that there is a "Void Problem", is that ΛCDM predicts the existence of many more dwarf galaxies than observed. Does it?



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The "Minihalo Chase"…

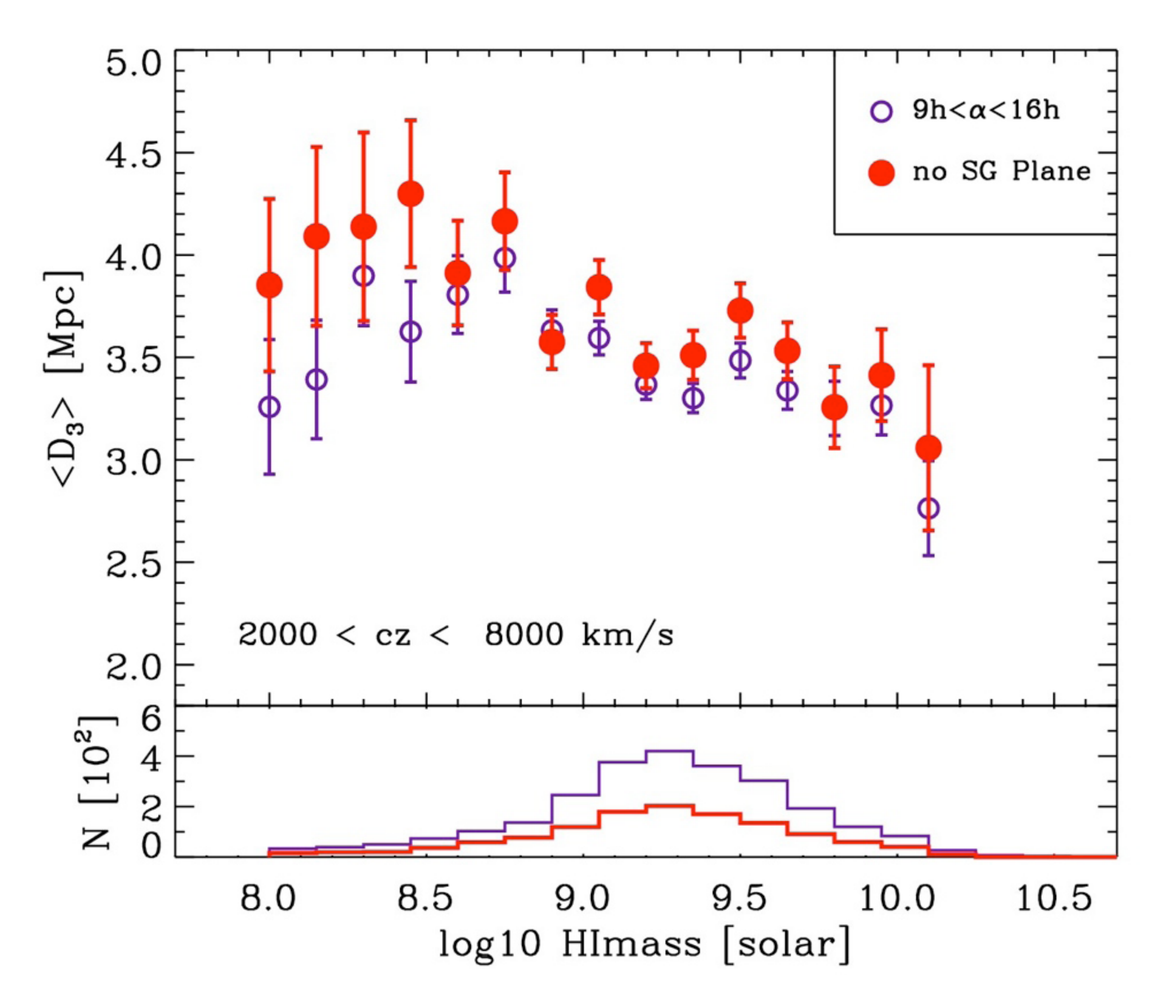
- *Simulations indicate that low mass halos are abundant*
- *They also suggest that baryon retention weakens as halo mass decreases*
- *This qualitatively explains mismatch between (shallow) observed faint slopes of opt LF and HIMF and (steep) halo mass function ➔ need to verify prediction*

➔Q: at what halo mass does the baryon fraction start to diminish?

➔Q: at a given halo mass, what fraction of the baryons are in a detectable phase?

➔Q: how deep do we need to go before we sample the dwarf systems which, e.g., are thought to fill the voids?

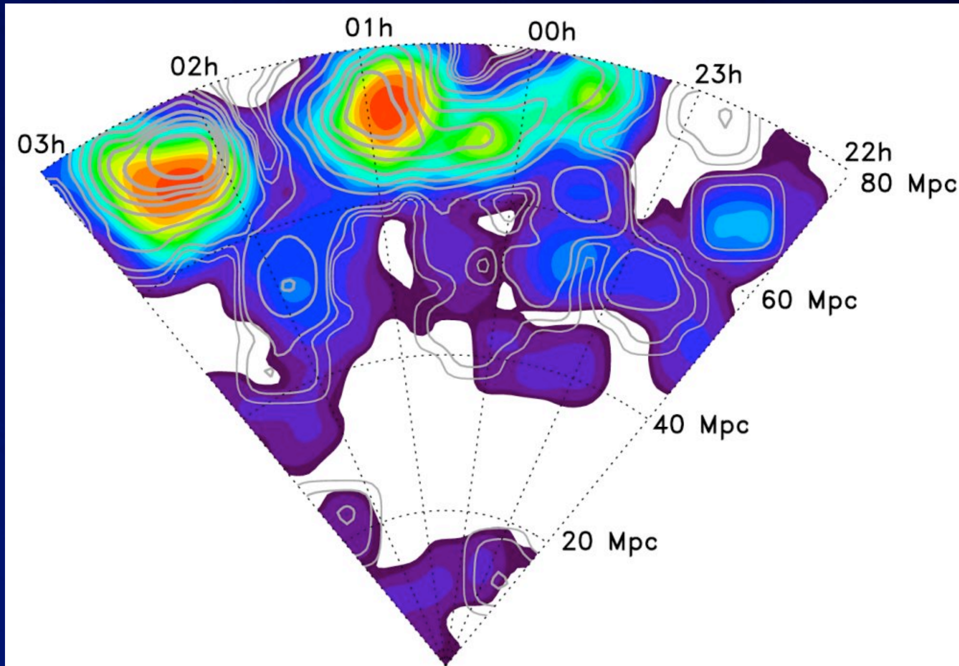
ALFALFA HI sources – Mean distance to 3d nearest neighbor



Within the pop. of gas-rich systems, lower HI mass systems tend to favor inhabiting the lower density regions.

Amelie Saintonge, 2009 in preparation

ALFALFA



ALFALFA – PP Void

Decs 24º to 32º

(22% of void coverage)

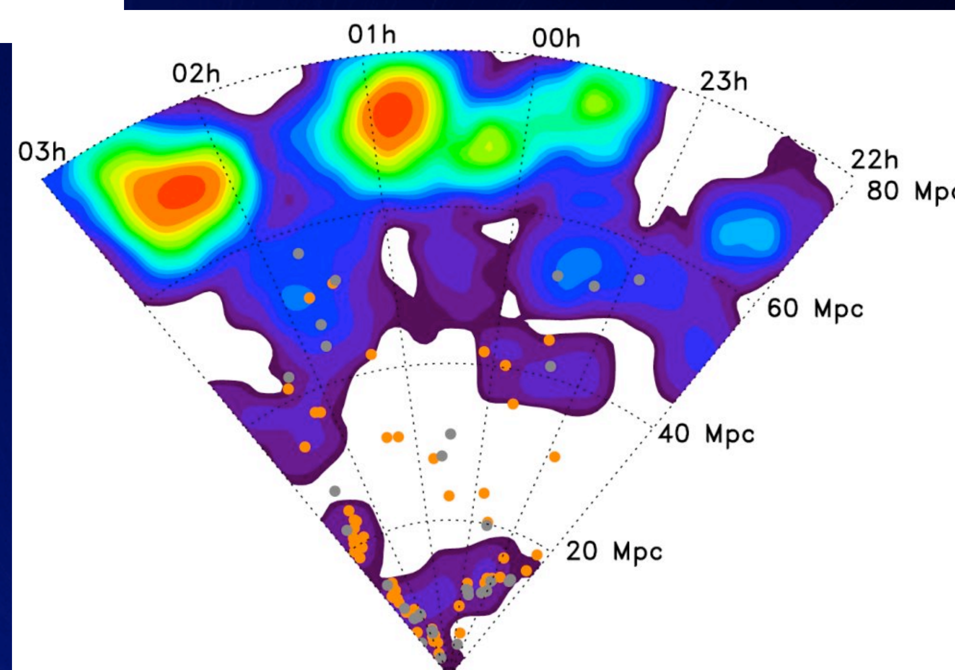
Amelie Saintonge 2009, in preparation

←*Grey contours: optical volume limited at M_B = -19.0*

←*Color contours: HI volume limited at M_HI =$10^{9.2}$ solar*

Grey dots: optical galaxies with M_B > -18. →

Orange dots: HI galaxies with M_{HI} < 10^8 Msun



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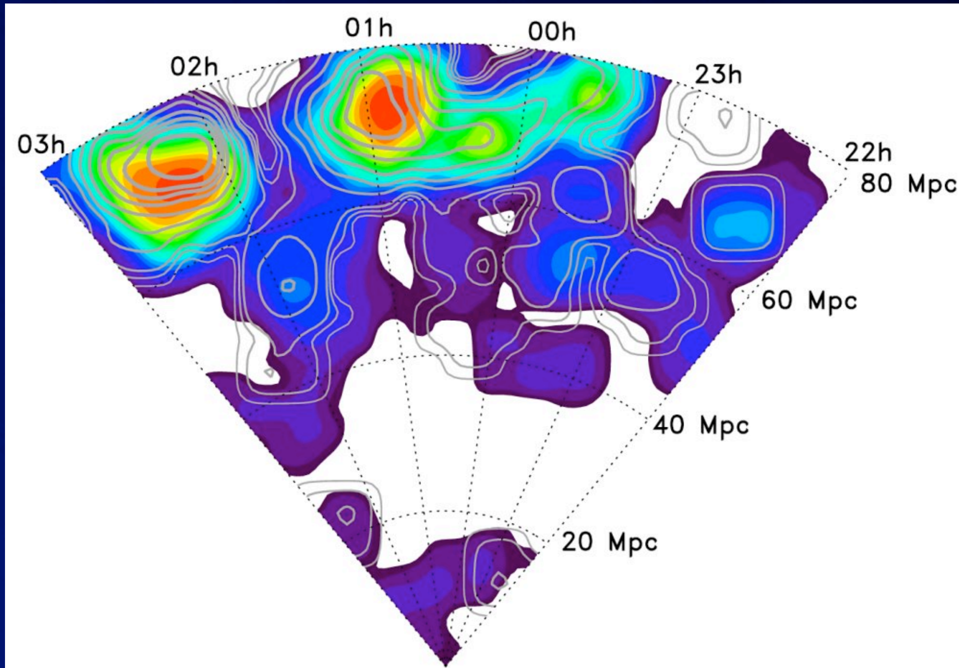

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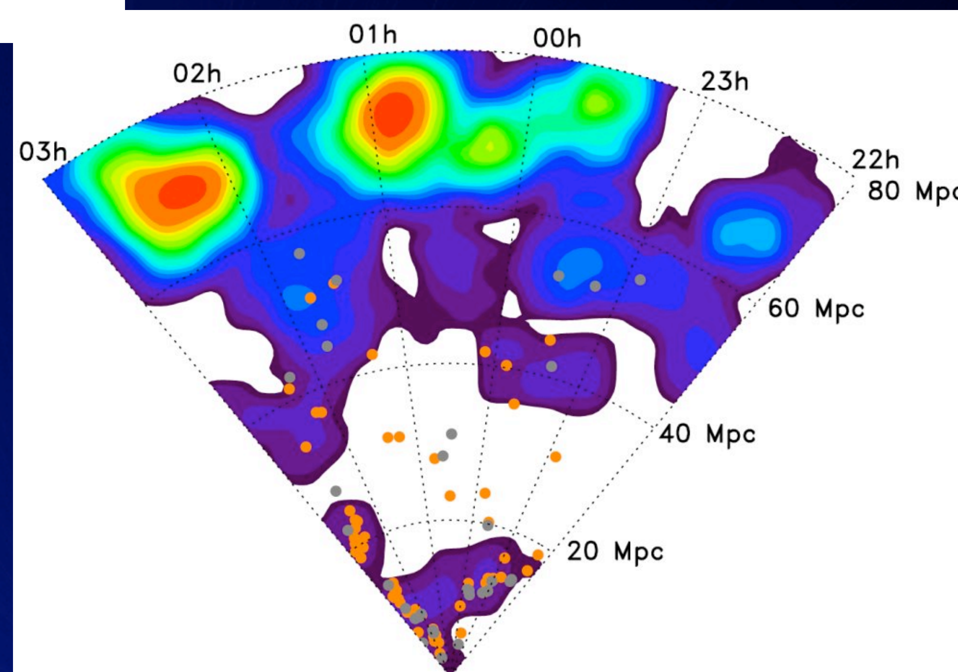

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...far from filling the voids

ALFALFA

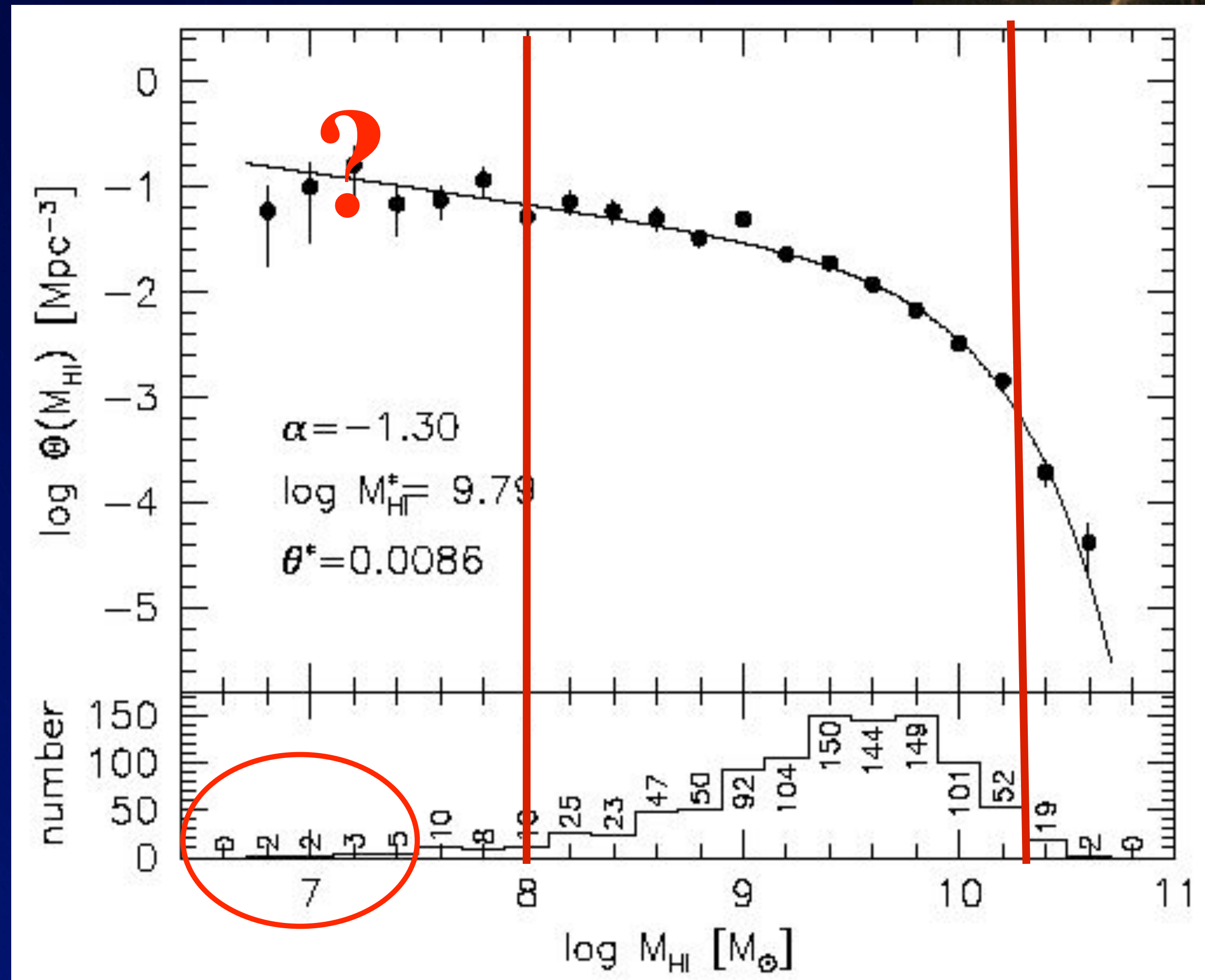
The HI Mass Function

- Previous surveys have included few (if any) objects with HI masses less than $10^8\ M_\odot$.
- At lowest masses, differ by 10X:

  Rosenberg & Schneider (2000)

  versus

  Zwaan et al. (2003)



Parkes HIPASS survey:
Zwaan et al. 2006

ALFALFA

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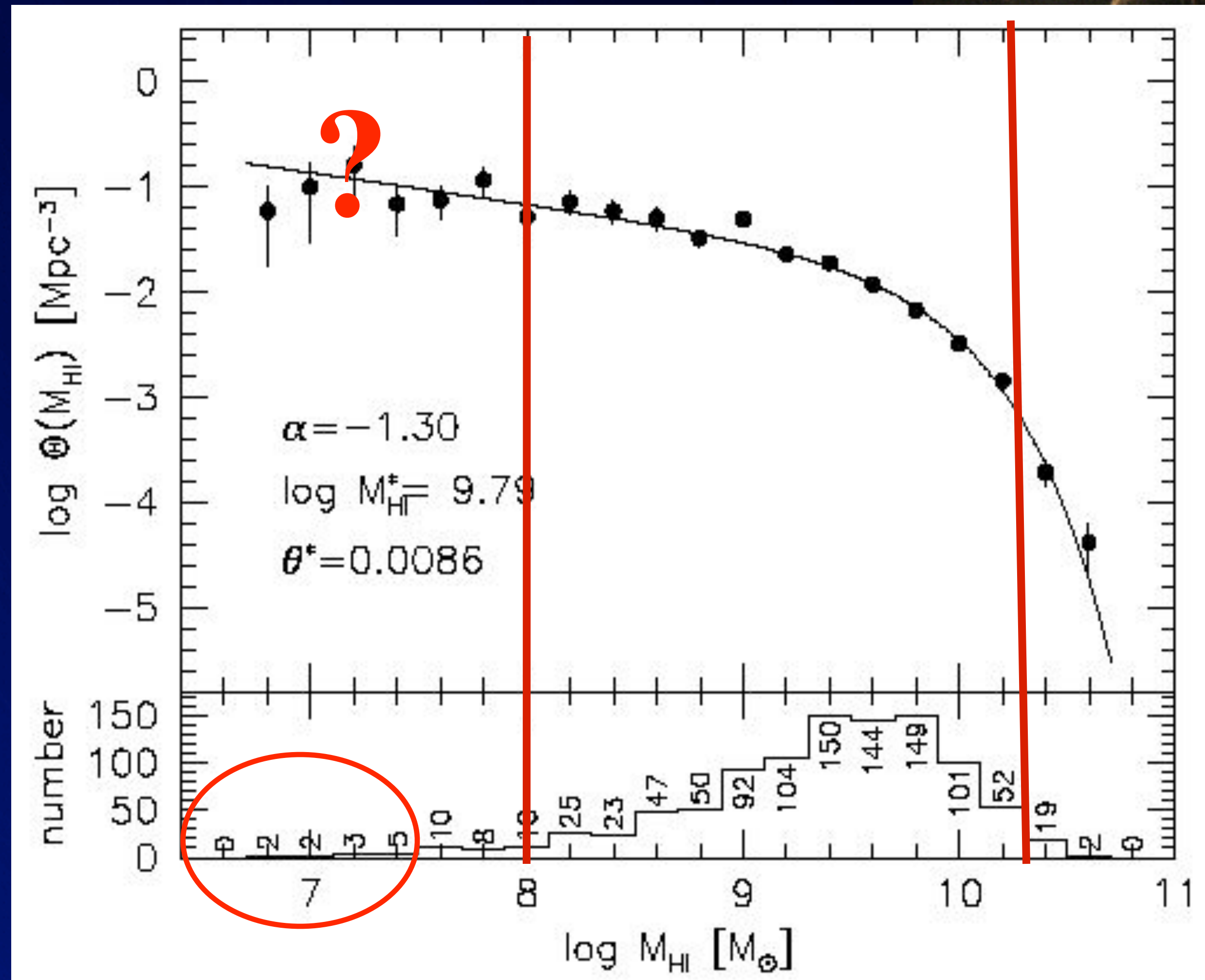

- Statistics
- Systematics

Parkes HIPASS survey:
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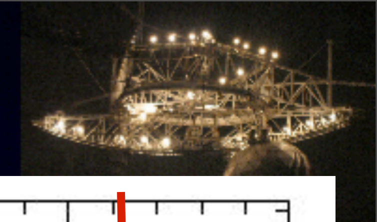
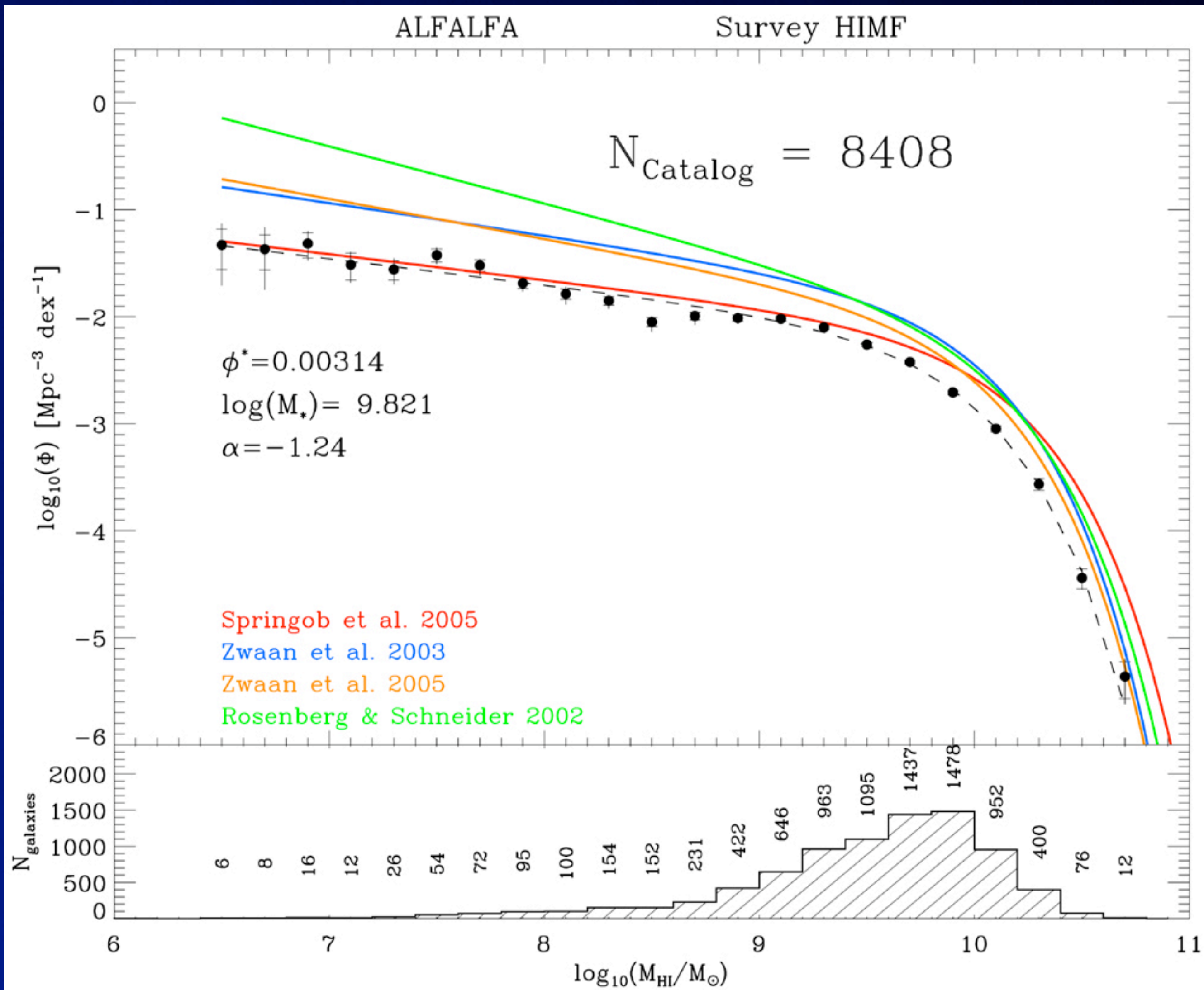


ALFALFA

ALFALFA HI Mass Function

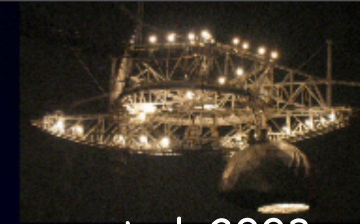
Ann Martin 2009
in preparation

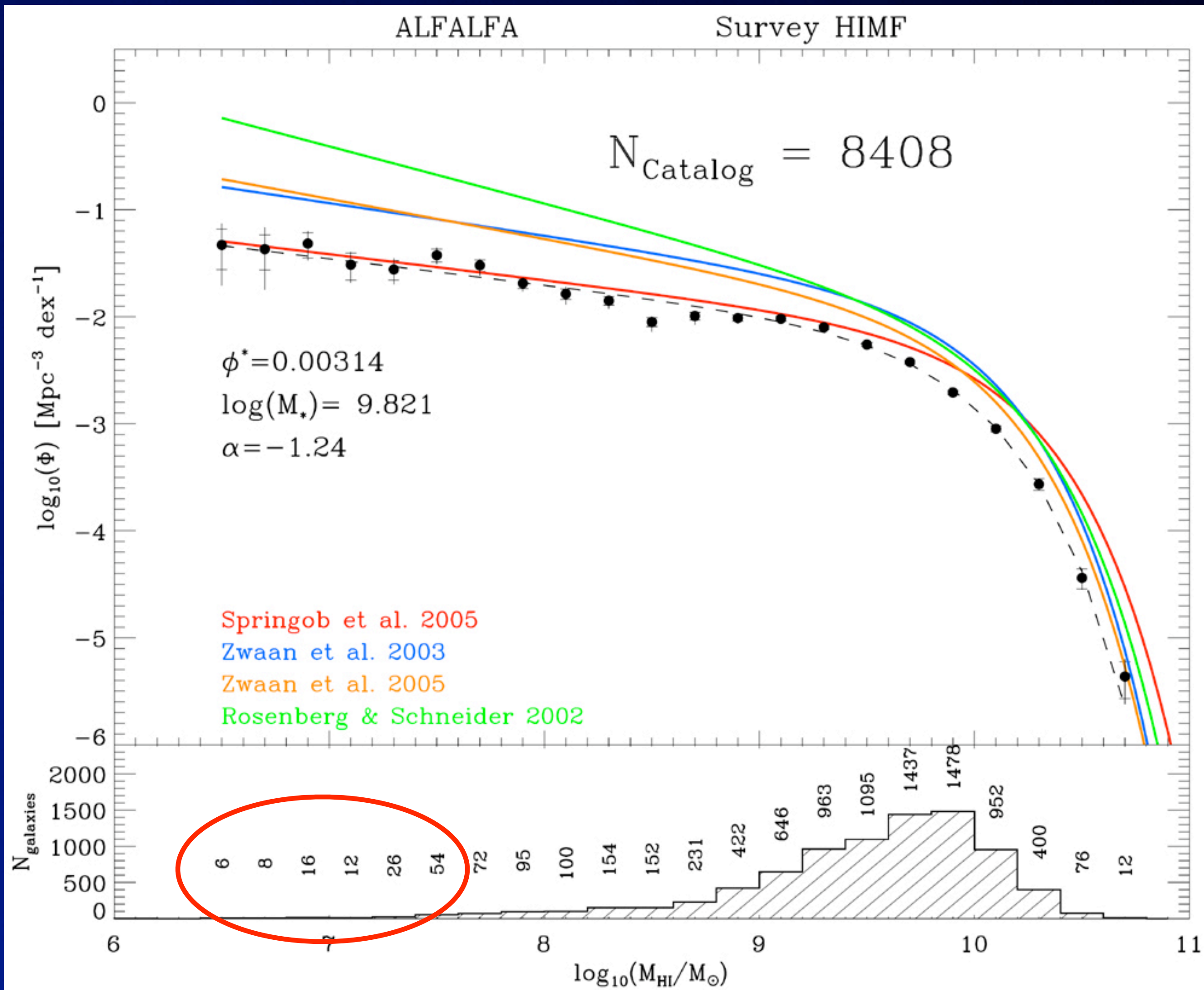


ALFALFA

ALFALFA HI Mass Function

Ann Martin 2009
in preparation





The Zwaan et al. 2003 HIMF, based on HIPASS, includes **12** galaxies with

log M_HI < 7.5

With <1/4 of ALFALFA processed, we have **122**

ALFALFA HI Mass Function

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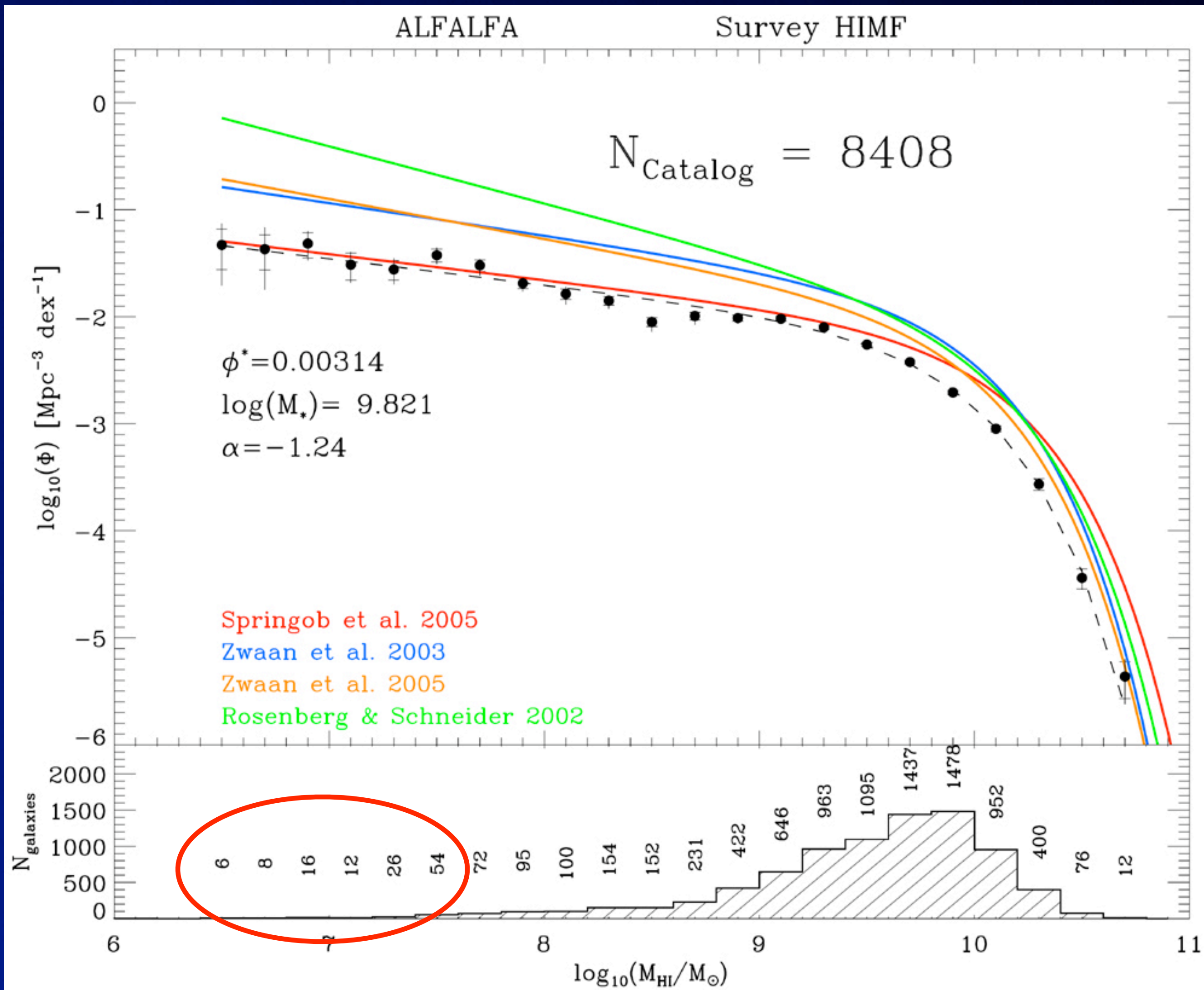

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With <1/4 of ALFALFA processed, we have **122**

…however, no overabundance of faint, HI-rich galaxies

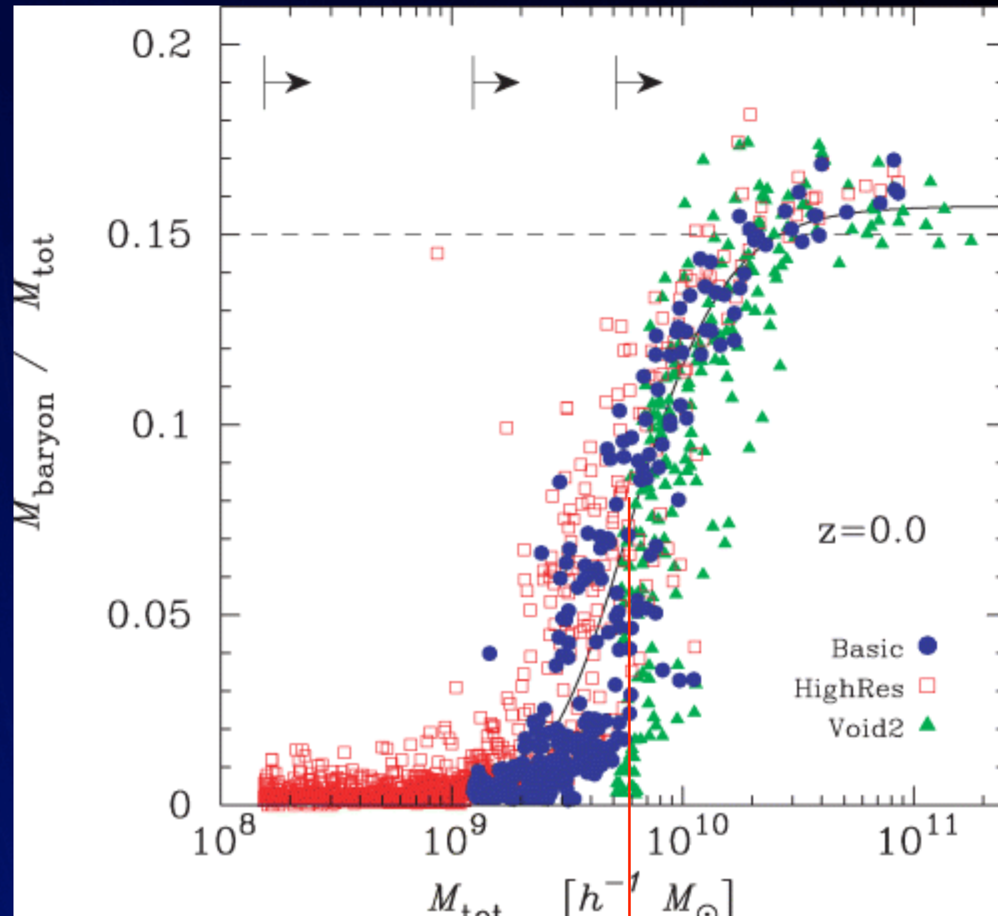
Vertiginous drop in baryon fraction predicted

Vertiginous drop in baryon fraction predicted

*-**Hoeft et al. (2006)** simulated the SF processes, using code that included radiative processes, SN feedback and an external, photoionizing Hardt & Madau (1996) UV background, with a resolution that allows monitoring evolution of DM halos of mass as low as **2.3x10⁸ Msun**.*

- <u>Small halos DO NOT retain their share of baryons</u>
➔

*- Note dependence on simulation **resolution***



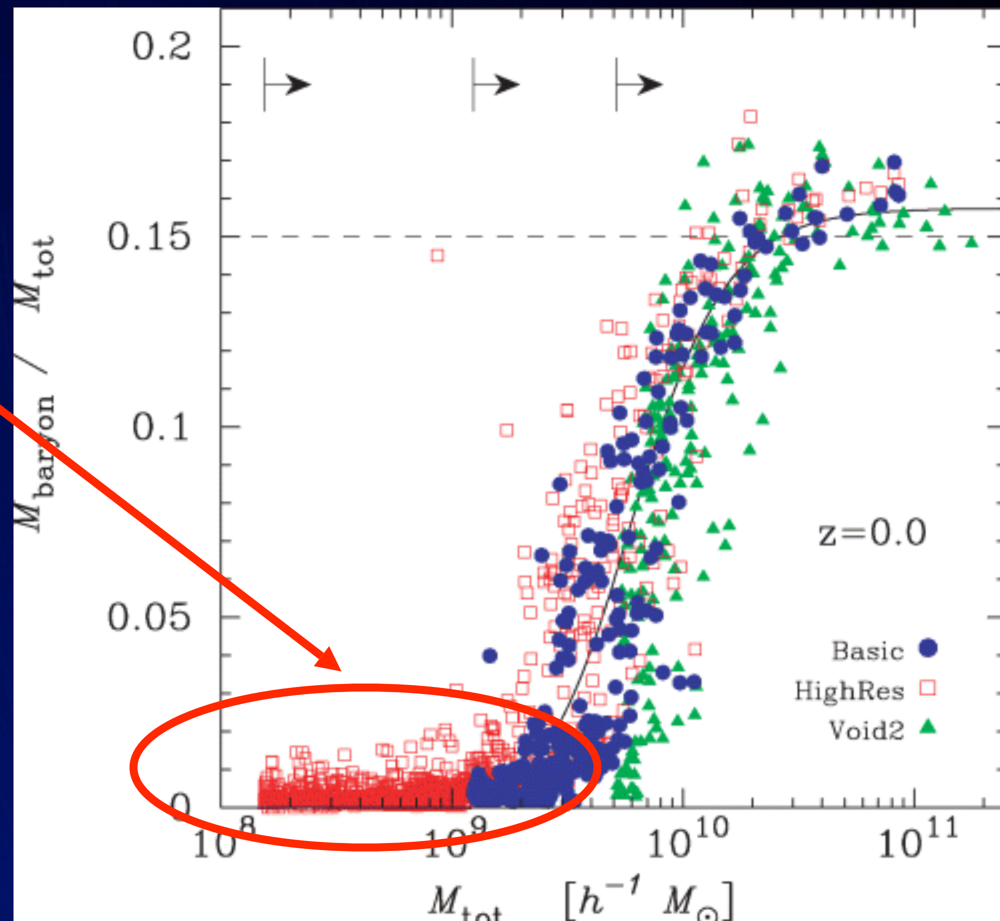
Characteristic halo Mass M_c : that which retains 50% of its baryons

ALFALFA

Do we have any chance to ever observe these guys?
10^9 msun halo → < 10^7 msun baryons

Sternberg, McKee & Wolfire (2002) *have investigated the gastrophysics of minihalos: the remaining baryons in a low mass halo are capable of developing a small WARM NEUTRAL phase (WNM), possibly detectable through its HI emission.*

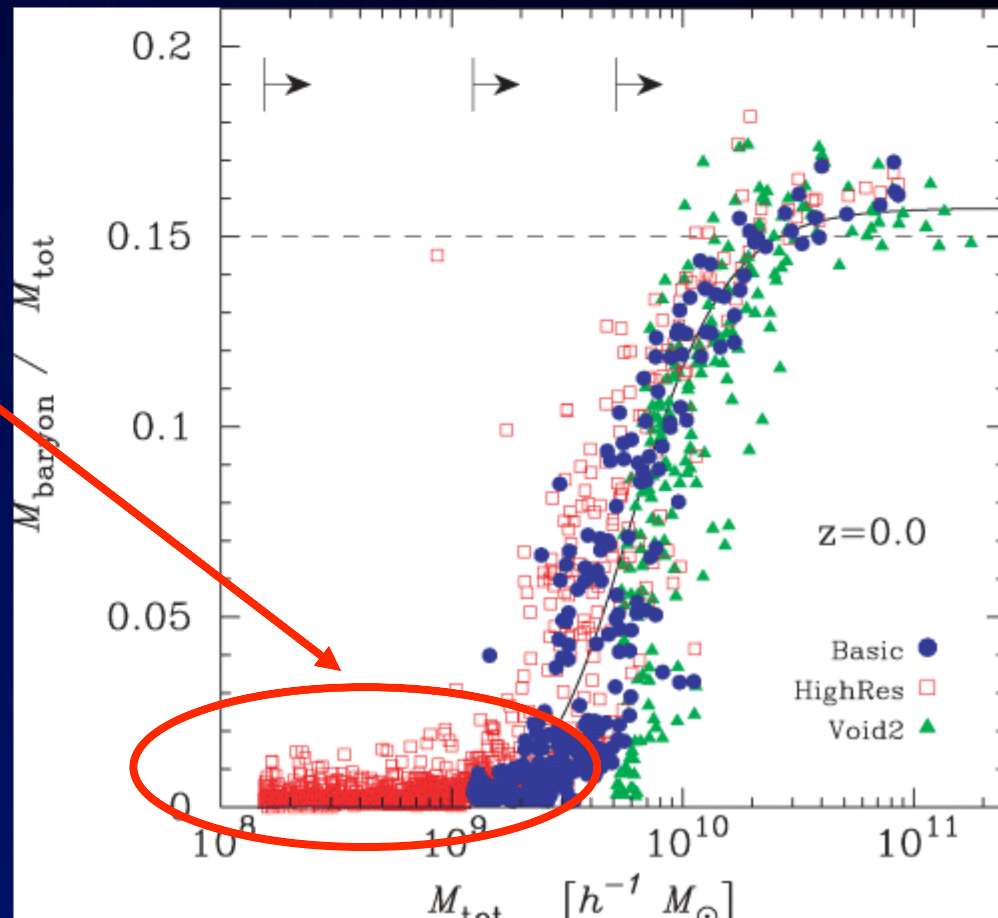
… 'though HI mass is only a fraction of baryon mass



ALFALFA

…it gets harder: we need to go fainter than 10^6 M_{sun}

Do we have any chance to ever observe these guys?
10^9 msun halo → < 10^7 msun baryons



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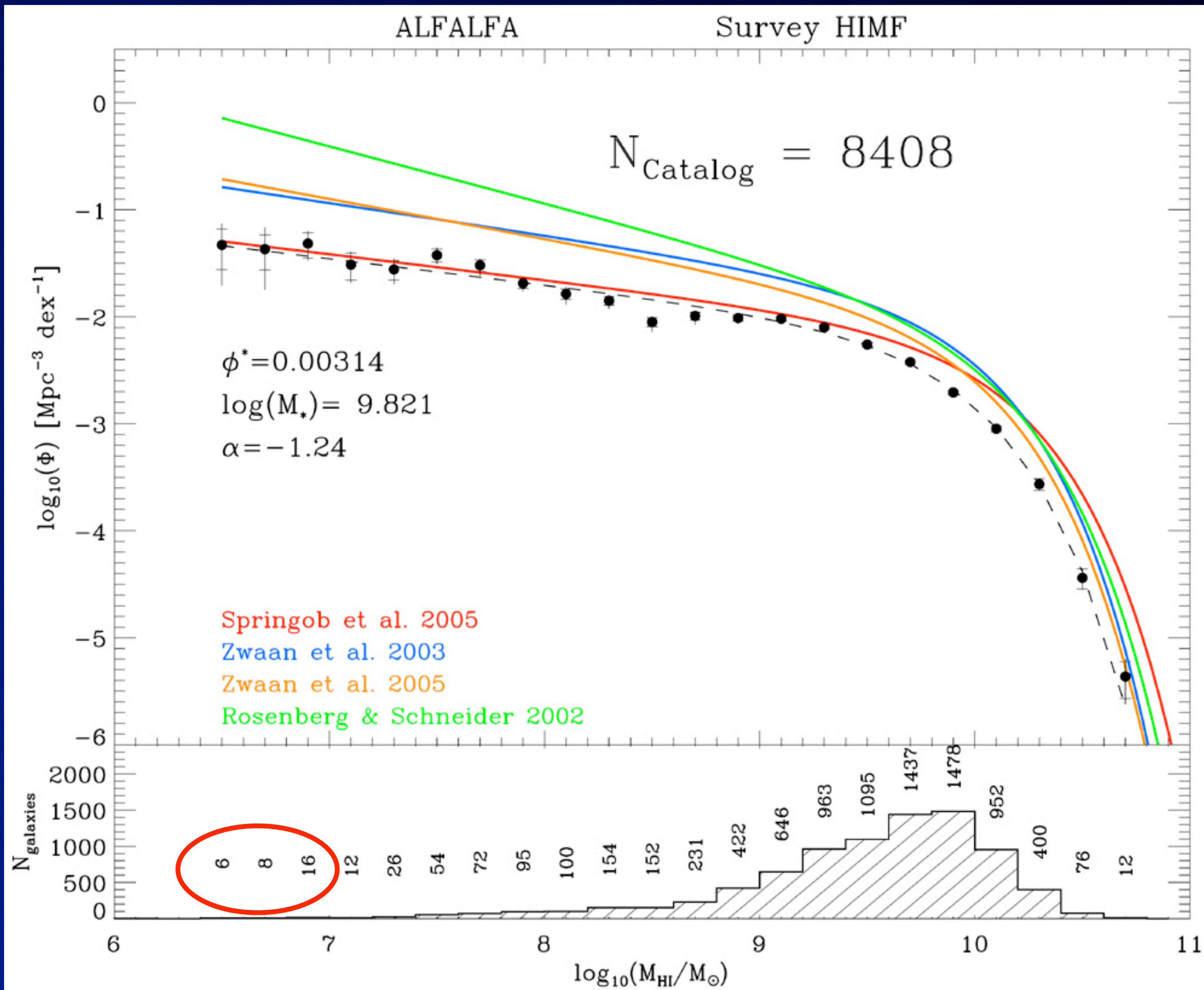
ALFALFA

ALFALFA HI Mass Function



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Even ALFALFA detects very few sources with

$M_{HI} < 10^7$ Msun

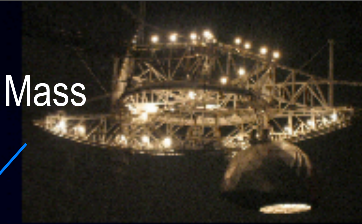
And it does so only at D<13 Mpc

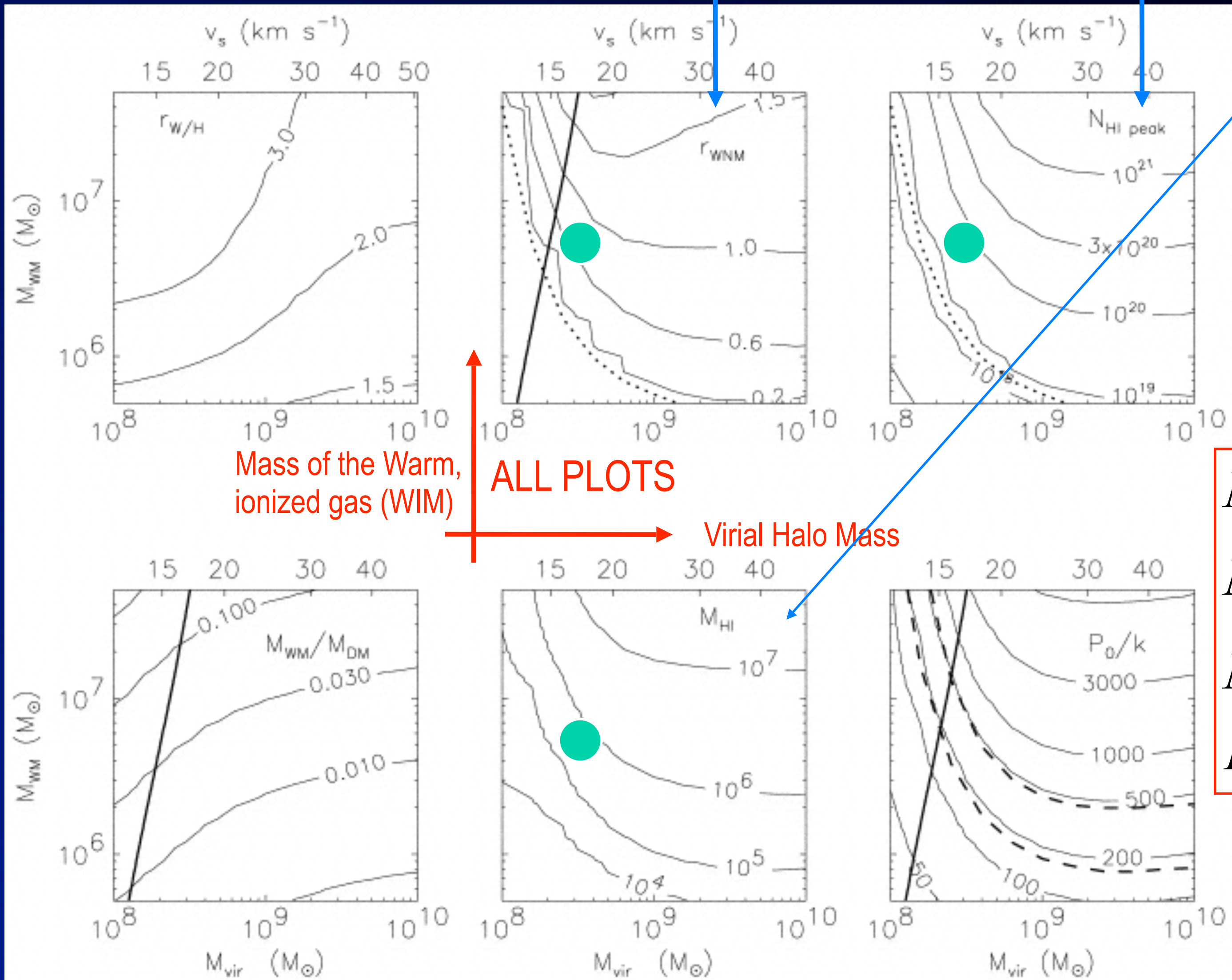
Sternberg, McKee & Wolfire 2002

Contours of HI (WNM) radius (kpc)

HI column density

HI Mass





Mass of the Warm, ionized gas (WIM)

ALL PLOTS

Virial Halo Mass

A possible model for a baryon-poor minihalo:

$$M_{halo} = 3\times10^8 M_{sun}$$
$$M_{baryon} = 5\times10^6 M_{sun}$$
$$M_{HI} = 3\times10^5 M_{sun}$$
$$R_{HI} = 0.7 kpc$$

ALFALFA

Even ALFALFA cannot detect
$M_{HI} = 3x10^5$ Msun
farther than 2-3 Mpc…

Even ALFALFA cannot detect
M_{HI} = 3x10^5 Msun
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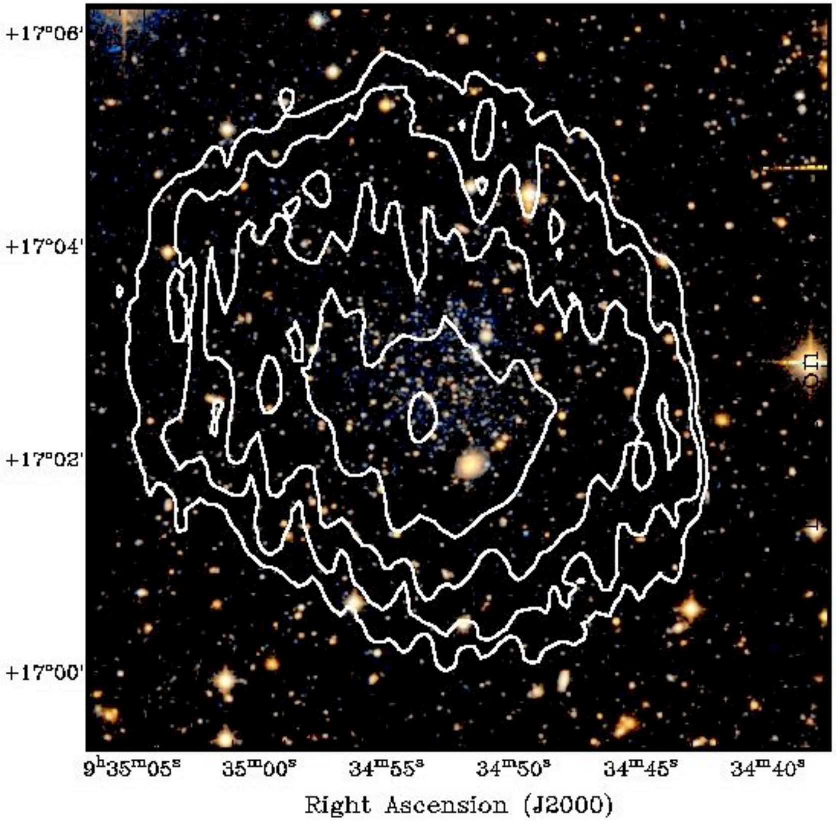
… so let’s look nearby

WSRT observations

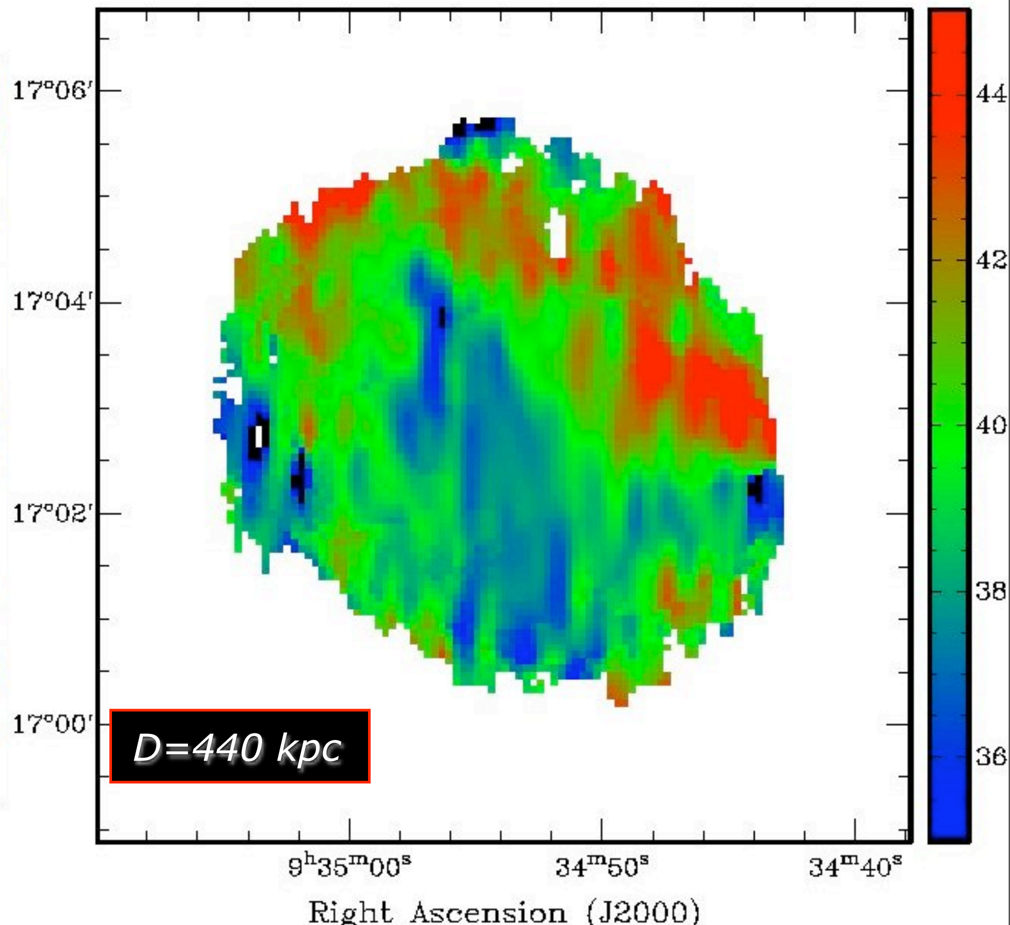
- Nice, regular HI distribution. Some rotation???????
- H I velocity matches optical velocity: 39 vs 38 km s^{-1}
- Velocity dispersion H I: 7 km s^{-1}, stars 8 km s^{-1}
- $M_{dyn}/L_V \sim 125$

HI mass = 3x10^5 Msun
HIMass/L_V = 5
M_dyn=8x10^6 Msun
… and still forming stars…
[80% of visible baryons in HI]

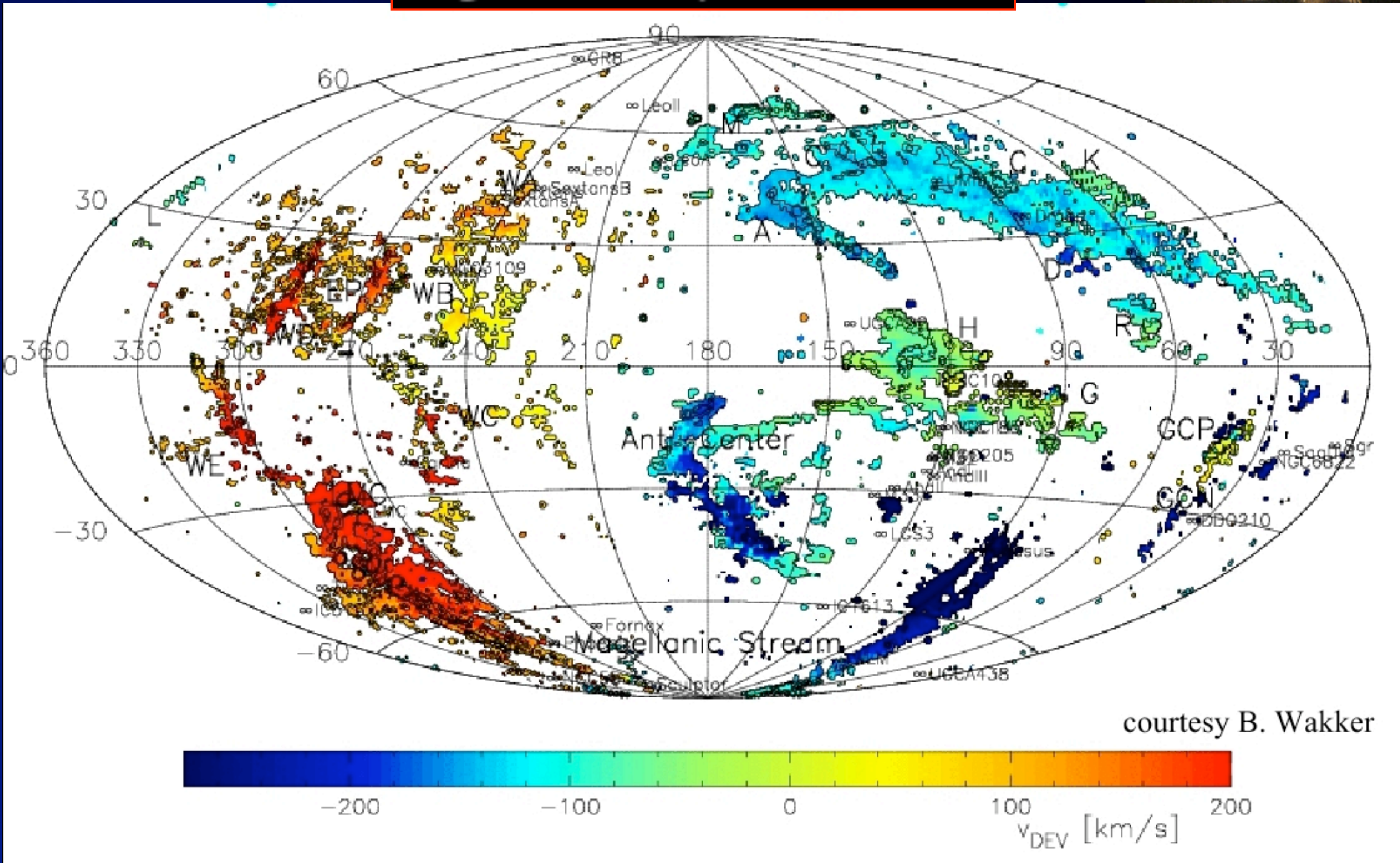
Credit: T. Osterloo, Spineto 2007



contours 2, 5, 10, 20, 50 · 10^{19} cm^{-2}



High Velocity HI Clouds



ALFALFA

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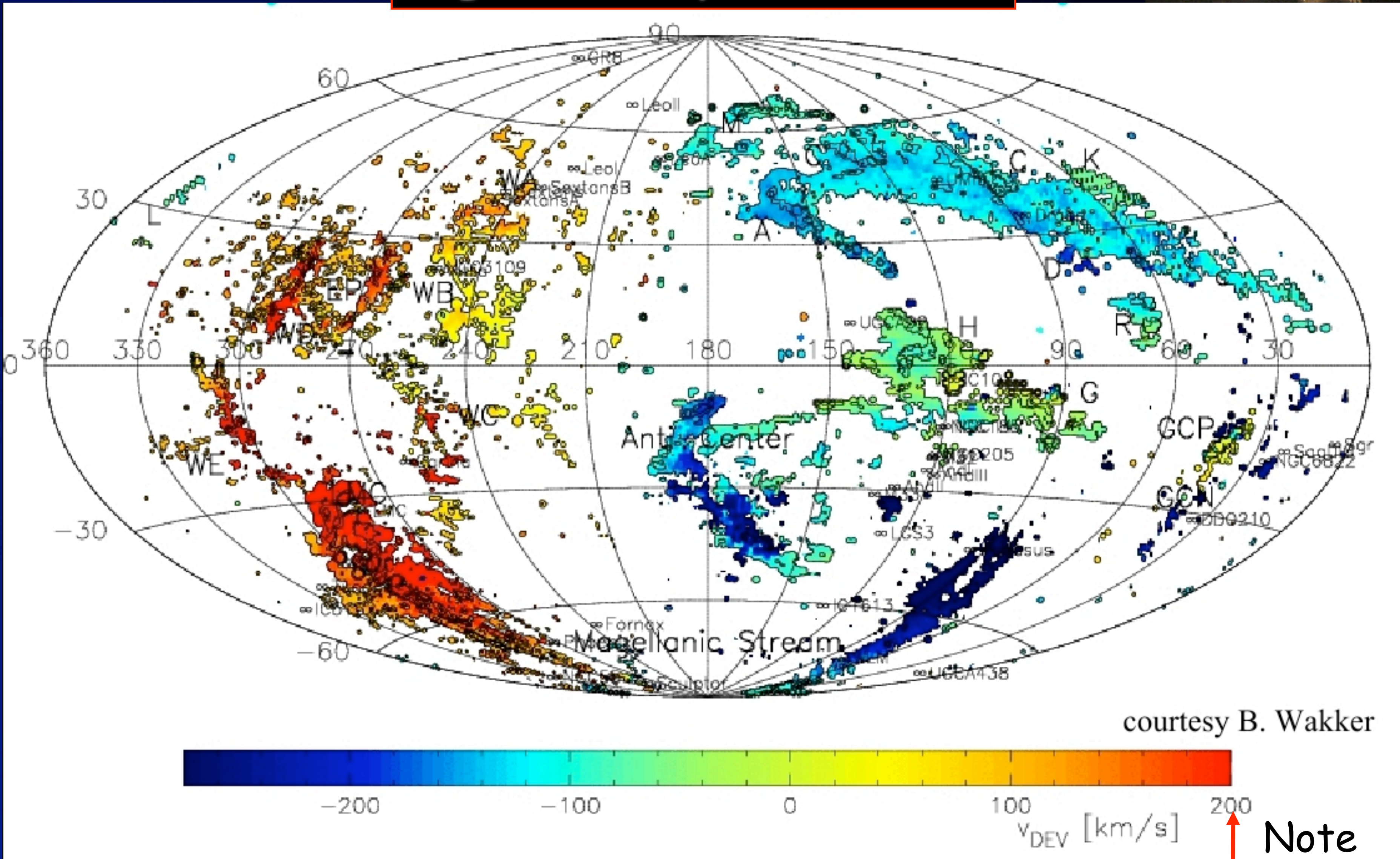

Note

HVCs: an Intergalactic Population?

Blitz et al (1999)*:"* *HVCs are large clouds, with typical diameters of 25 kpc, containing $3x10^7$ solar of neutral gas and $3x10^8$ solar of dark matter, falling towards [the barycenter of] the Local Group; altogether the HVCs contain 10^{10} solar of neutral gas."*

Braun & Burton (1999): The "undisturbed" minihalos appear as **Compact HVCs**, which have typical sizes of 0.5 deg and FWHM linewidts 20-40 km/s

Problems:

If HVCs (or CHVCs) are bona fide LG members, they should also exist in galaxy groups other than the LG: NOT SEEN

2. Sternberg et al (2002) *show that, in order to fit DM halo models to the CHVCs, their HI fluxes and angular sizes constrain them to be* ***no farther than 150 kpc****, else they famously violate the ΛCDM mass-concentration relation:* ***CHVCs ARE TOO LARGE***

ALFALFA

Select a quiet, uncrowded piece of high galactic latitude sky covered by ALFALFA and find whether there are any Ultra Compact HVCs with properties such that, if placed a D~1 Mpc, they are compatible with minihalo models?

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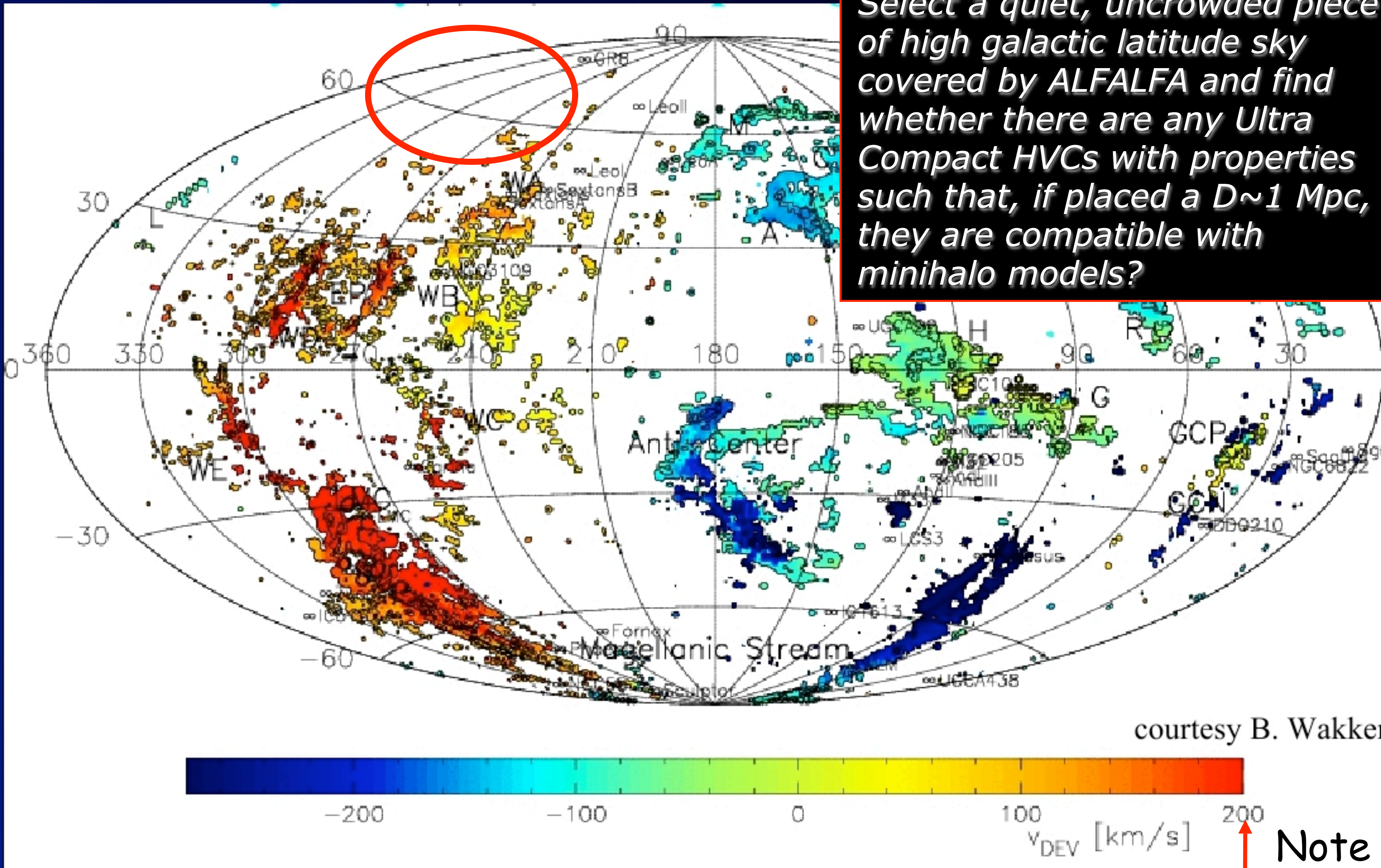
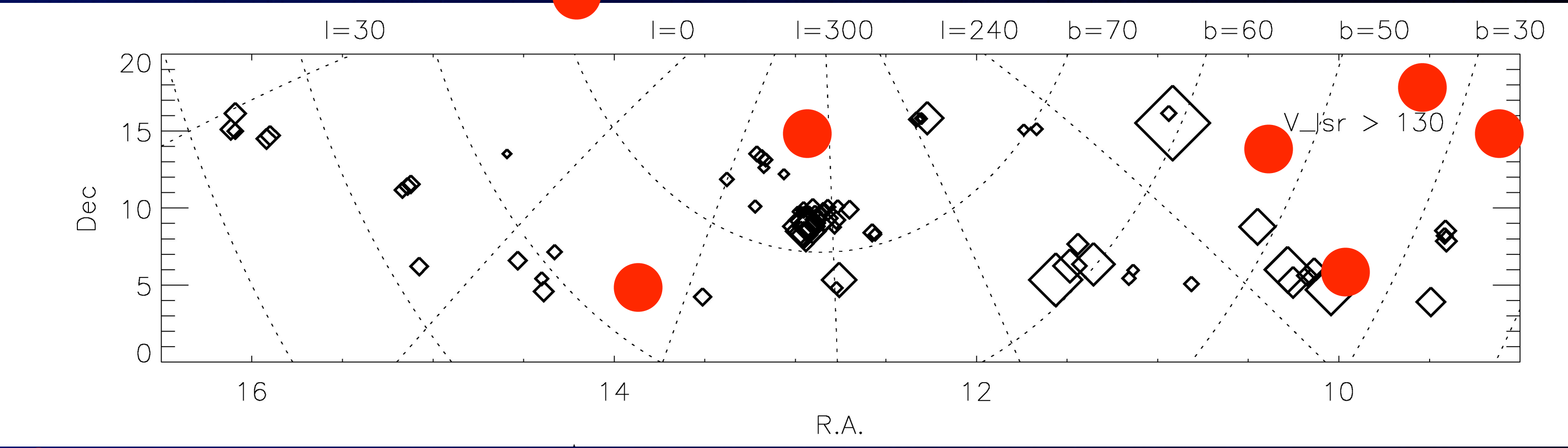
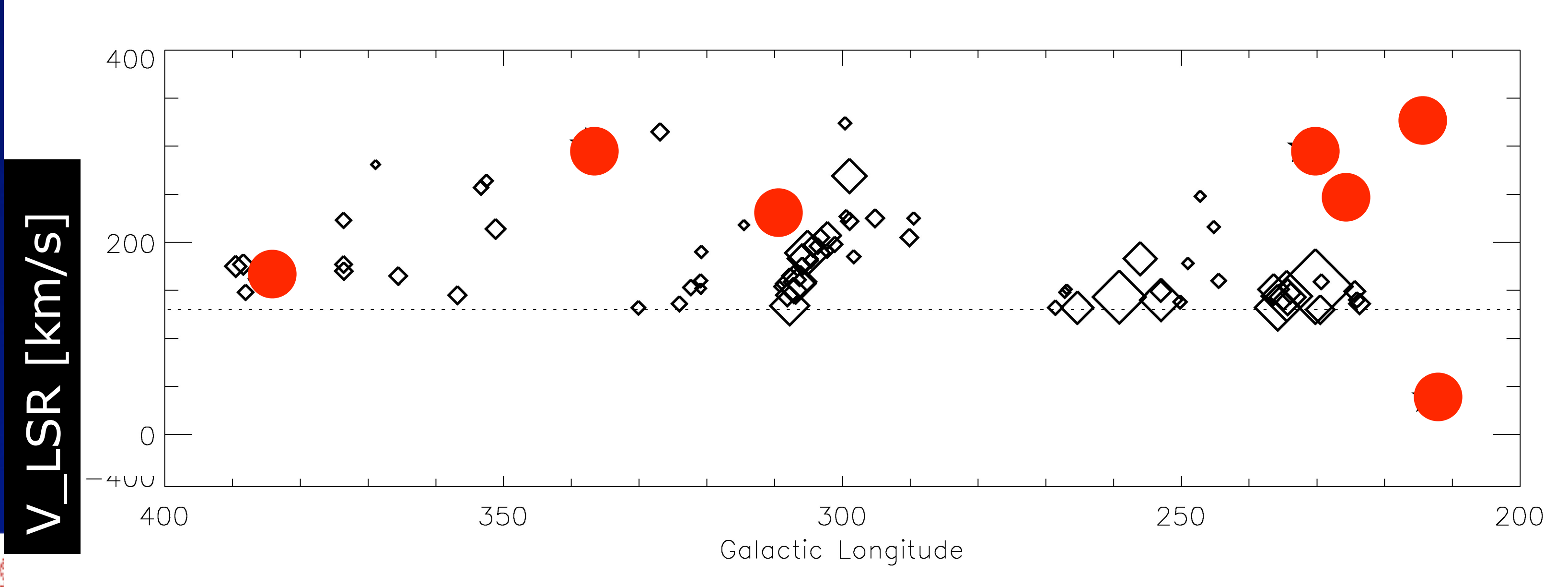


HVCs in footprint of ALFALFA, North Galactic Cap

Ω = 1620 sq deg

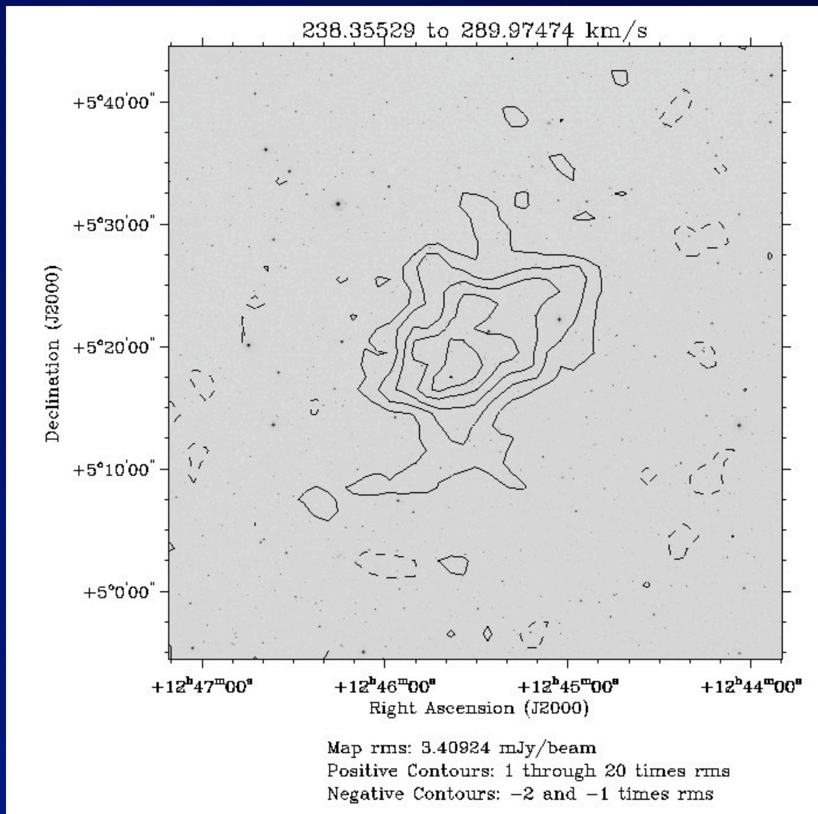


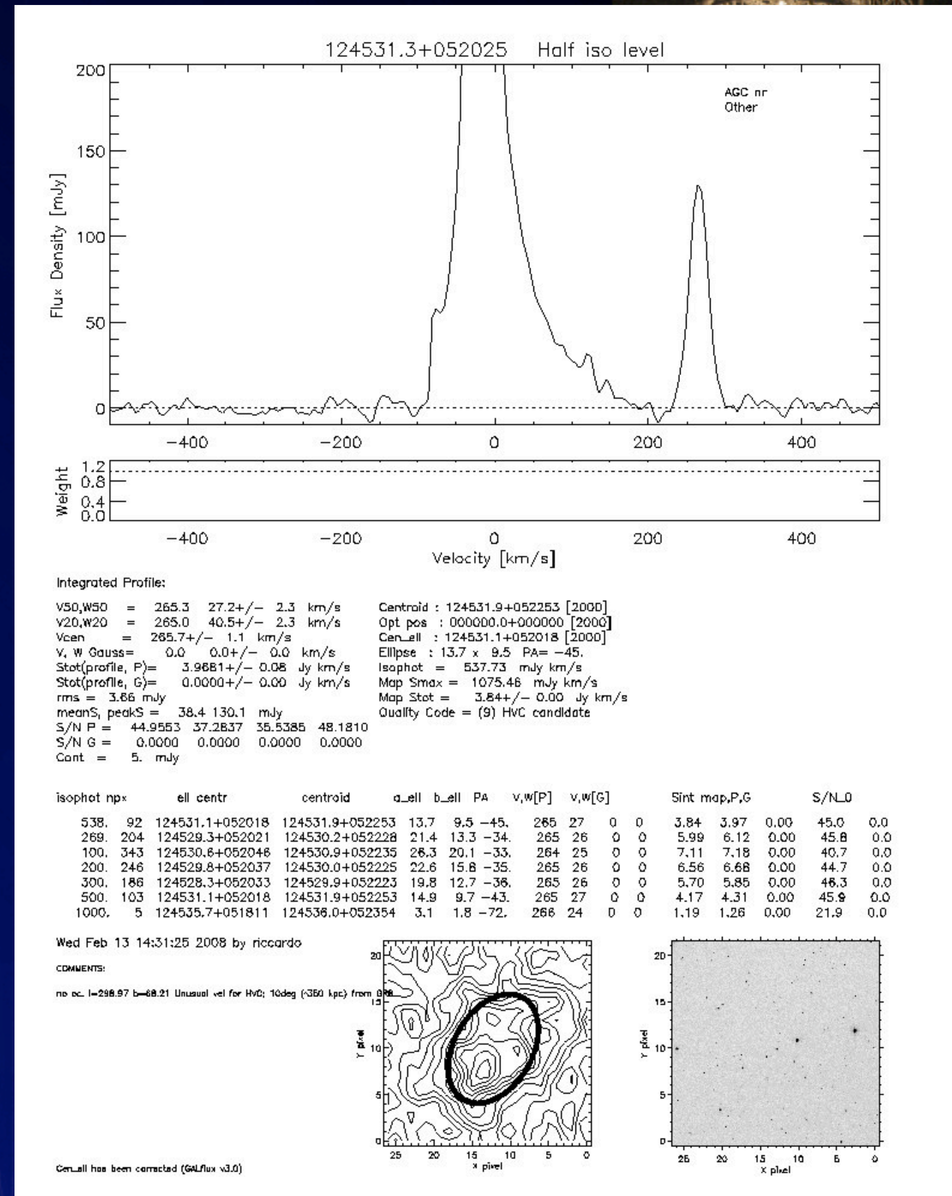
LG galaxies within D=2.6 Mpc (away from center of LG)



ALFALFA

About 20 very compact clouds are found, several unresolved at 4′ …





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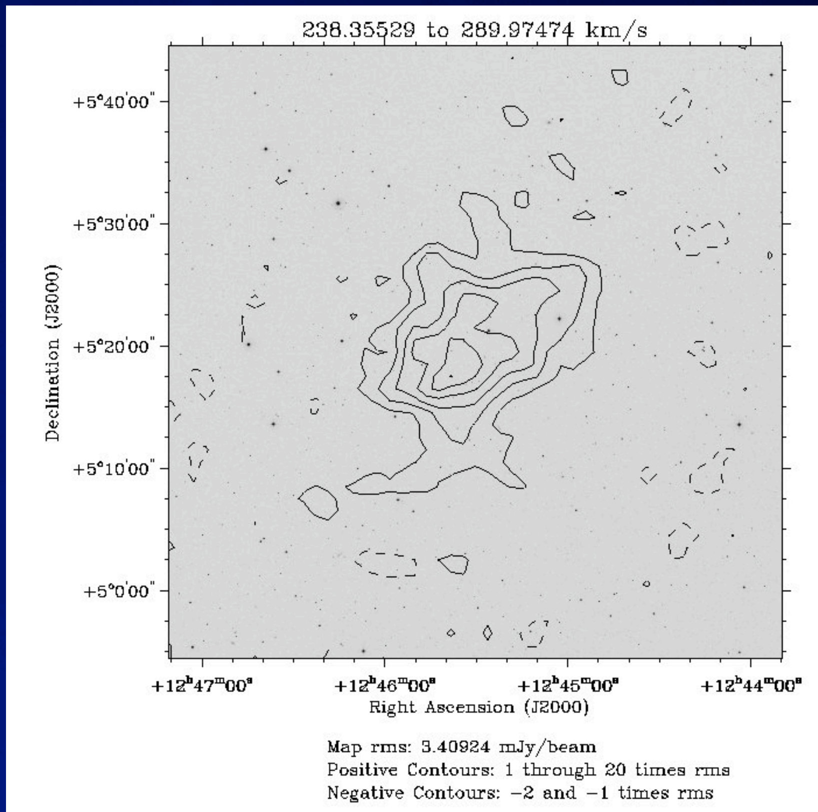

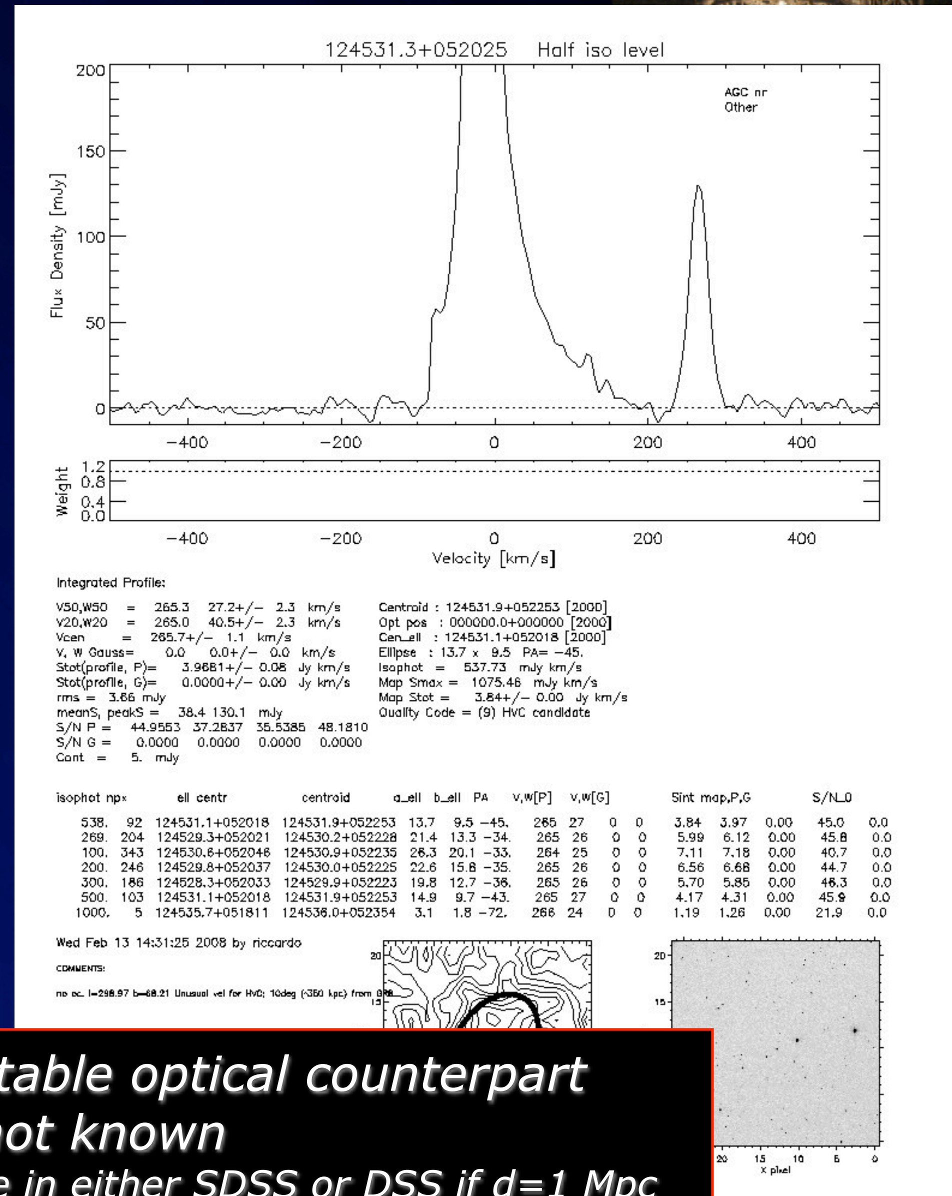

None has (so far) a detectable optical counterpart

Distances are not known

Note: Leo T would not be detectable in either SDSS or DSS if d=1 Mpc

ALFALFA

ALFALFA Minihalo Candidates at D=1 Mpc

- Mean HI Mass 3×10^{5} solar
- Mean HI Diameter 0.7 kpc
- Mean avged HI column density $10^{19.1}$ cm^{-2}
- Mean avged HI density 0.006 cm^{-3}
- Mean total mass within R_{HI} 3×10^{7} solar

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Sternberg et al (2002) Minihalo Template @ P=10 cm^{-3} K

• HI Mass	3×10^{5} solar
• HI Diameter	0.7 kpc
• Peak HI column density	$10^{19.6}$ cm^{-2}
• WIM Mass	6×10^{6} solar
• Total mass within R_{vir}	3×10^{8} solar

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At the distance of nearby groups of galaxies, the ALFALFA minihalo candidates would have been below the sensitivity limit of extant HI surveys.

ALFALFA

We have found a subset of the HVC phenomenon that appears to be compatible with the minihalo hypothesis.

Other interpretations are possible, we have not proved that the candidates are LG minihalos, but that is a tantalizing possibility.

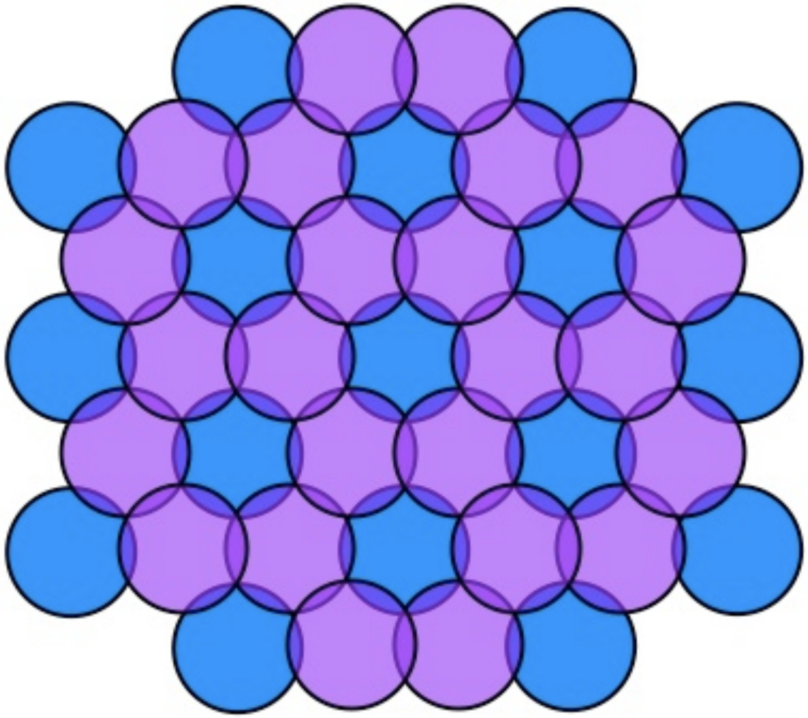
We need to detect similar features in nearby galaxy groups. That will require significant increase in telescope survey speed.

the Depth of the survey increases only as

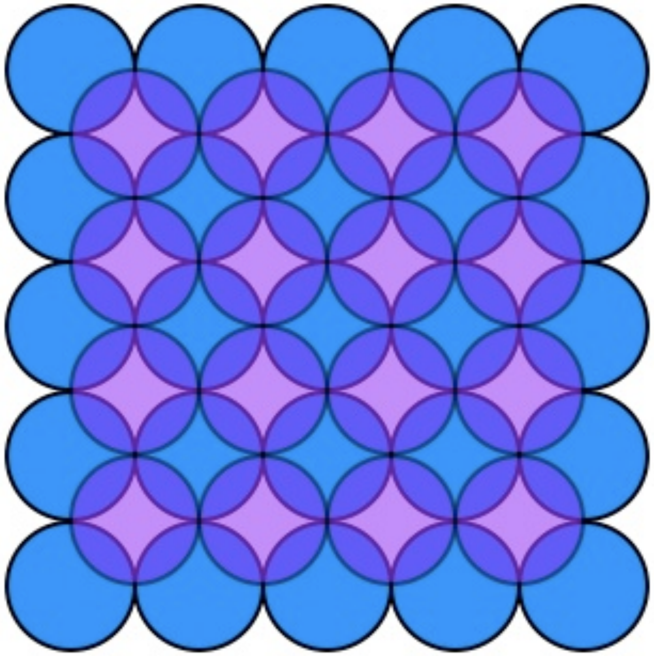
$$D_{Mpc} \propto t_s^{1/4}$$

ALFALFA

AO FPA Sky Footprint Layout



Hexagonal
41 Beams



Rectangular
41 Beams

Credit: German Cortes, NAIC

Survey Speed Figure of Merit

$$FoM \propto \left(\frac{A_{eff}}{T_{sys}} \right)^2 \Omega_{fov} BW$$

Parameters Used:

	D (m)	Beam	Ntel*Nbm	Tsys	BW
AO1	225	3.5’	1x1	25K	100MHz
ALFA	225	3.5’	1x7	30K	300
AO41	225	3.5’	1x41	50K	300
APERTIF	25	30’	14x25	50K	300
ASKAP	12	60’	30x30	50K*	300

(*) The actual performance that FPPAs will deliver is still very uncertain; Tsys values of 35K or 50K are rough expectations. It would be fair to use the same Tsys values for all telescopes → a value of 50K for ASKAP would then apply (they use 35K).

ALFALFA

Survey Speed Figure of Merit

$$FoM \propto \left(\frac{A_{eff}}{T_{sys}}\right)^2 \Omega_{fov} BW$$

	$(A_e)^2$	$(Tsys)^2$	FoV	BW	FoM
AO1	1	1	1	1	1
ALFA	1	1/1.4	7	3	14
AO41	1	1/4	41	3	31
APERTIF	1/41	1/4	1800	3	33
ASKAP	1/170	1/4	8800	3	37

ALFALFA

Instrumented with a ~40 beam FPPA, Arecibo would have a survey speed FoM comparable to ASKAP & APERTIF, with one important advantage: with a collecting area 10% of the SKA, the Arecibo telescope already exists.

One important disadvantage of AO: confusion limit will occur at much lower z than for distributed apertures like APERTIF and ASKAP.

➔ *Niche for AO41: large scale surveys of intrinsically weak sources at low z*

ALFALFA

Galactic Fountain

Clouds within a few kpc from MW plane:

➔ HI mass ~ solar, HI size ~ pc , t_{cross} < 1 Myr

Problems:

- *Velocities too high*
- *Very vulnerable to ram pressure, which will quickly slow them to terminal velocity*
- *Rapidly transient objects (age << ballistic timescale)*

Tidal stripping of gas outside the tidal radius of a cloud, where the tidal radius is

$$R_t = d\left[\frac{M_{c,tot}}{2M_{mw}(< d)}\right]^{1/3}$$

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27 minihalo candidates: What else can they be?

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27 minihalo candidates: What else can they be?

- Galactic Fountain
- Field of Streams
- Magellanic System
- Intergalactic gas accretion

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27 minihalo candidates: What else can they be?

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- Intergalactic gas accretion

What can destroy them?

- Evaporation
- Ram Pressure
- Tidal forces

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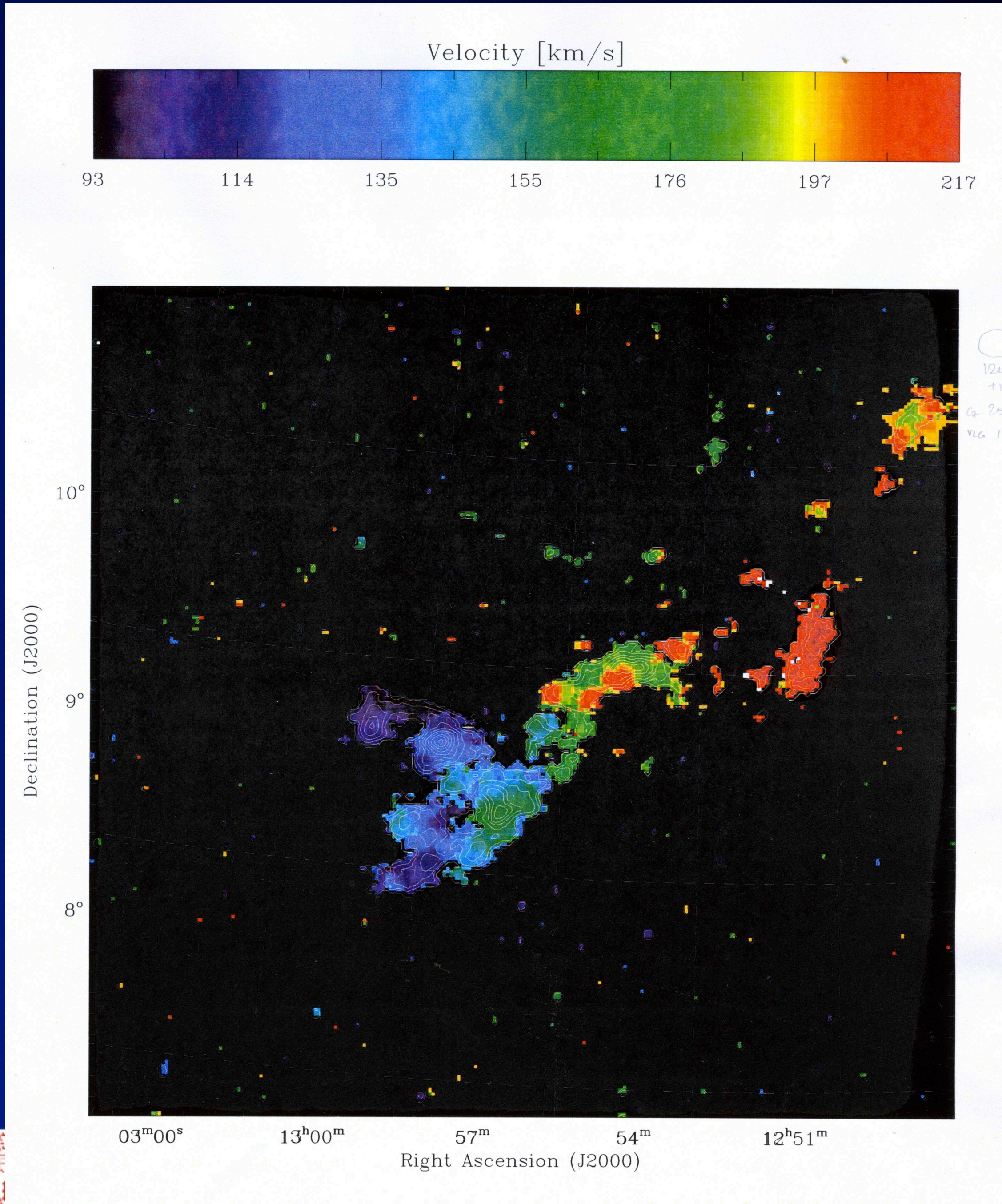
Field of Streams

Sky overlap with "Field of Streams" (Sagittarius and Orphan streams). However:

- *Similar objections to "fountain" scenario*
- *Inconsistent with optical stream kinematics*

ALFALFA


Velocity [km/s]
93
114
135
155
176
197
217
10°
9°
8°
Declination (J2000)
03^{m}00^{s}
13^{h}00^{m}
57^{m}
54^{m}
12^{h}51^{m}
Right Ascension (J2000)

Assume a Fukugita & Peebles (2006) Galactic corona, with $T=10^6$ K and radial profile:

$$n_{IGM}(r) = 4\times10^{-3}(r/10kpc)^{-3/2}\, cm^{-3}$$

… and adopt an IGM (beyond r=300 kpc) of $n_{IGM}=2.5\times10^{-5}$ cm^{-3}

and $T=10^6$ K

Thermal conduction will evaporate a cloud in a time:

$$t_{ev} \simeq 4.6\times10^3\,\mathrm{yr}\ \left(\frac{M_{HI}}{M_\odot}\right)\left(\frac{R_{HI}}{\mathrm{kpc}}\right)^{-1}\left(\frac{f_{c,gas}}{f_{cold}}\right)^{2/3} f_{mag}^{-1} T_6^{-5/2}$$

> t_Hubble at d=1 Mpc
~ 1 Gyr at d=100 kpc
Very short at d= 10 kpc

ALFALFA

Ram pressure will strip the gas from its DM halo if:

$$\left(\frac{n_{igm}}{10^{-3}\,\mathrm{cm}^{-3}}\right)\left(\frac{V}{10^{2}\,\mathrm{km\ s}^{-1}}\right)^{2} > \left(\frac{M_{c,tot}}{10^{8}M_{\odot}}\right)^{2}\left(\frac{R}{1\,\mathrm{kpc}}\right)^{-4}\left(\frac{M_{gas}}{0.01M_{c,tot}}\right)$$

A gravitationally unbound cloud of gas will be decelerated to terminal velocity by ram pressure in a time:

$$t_{ram} = \frac{V_c}{\dot{V}_{ram}} \simeq 2.7\times10^{3}\ \mathrm{yr}\frac{M_{c,gas}}{M_{\odot}}\left(\frac{n_i}{0.01}\right)^{-1}\left(\frac{R_{c,gas}}{\mathrm{kpc}}\right)^{-2}\left(\frac{V_c}{\mathrm{kms}^{-1}}\right)^{-1}$$

…where the terminal velocity is:

$$V_t \simeq 0.6\ \mathrm{kms}^{-1}\ \left(\frac{M_{c,gas}}{M_{\odot}}\right)^{1/2}\left(\frac{R_{c,gas}}{\mathrm{kpc}}\right)^{-1}\left(\frac{d}{\mathrm{kpc}}\right)^{-1/2}\left(\frac{n_i}{0.01}\right)^{-1/2}$$

ALFALFA